Joint ADVISOR/PSAT Vehicle Systems Modeling User Conference

2001 ADVISOR/PSAT User Conference

Proceedings

August 28-29, 2001
Southfield, Michigan

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Swami Gopalswamy, Emmeskay Inc.

Fuel Cell Hybrid Vehicle Systems Analysis

Degree of Hybrization ADVISOR Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle
Paul Atwood, Stephen Gurski, and Doug Nelson, Virginia Polytechnic University;
Keith B. Wipke and Tony Markel, National Renewable Energy Laboratory

Aymeric Rousseau, Rajesh Ahluwalia, Howard Geyer, and Keith Hardy,
Argonne National Laboratory

Wednesday Special Presentation

Tony Markel, National Renewable Energy Laboratory

2001 ADVISOR/PSAT User Conference

Opening Address

Opening Address: 2001 Joint ADVISOR/PSAT Vehicle Modeling Users Conference

Robert Kost, Vehicle Systems Team Leader and
Patrick Sutton, Vehicle Systems Analysis Program Manager,
US Department of Energy

Opening Address

2001 Joint ADVISOR/PSAT Vehicle Modeling Users Conference

Pat Sutton
Vehicle Systems Analysis Program Manager
Office of Advanced Automotive Technologies
Office of Transportation Technologies
U. S. Department of Energy

USCAR
Southfield, Michigan
August 28 - 29, 2001

Office of Transportation Technology Objective

➢ Work in Partnership with Stakeholders to reduce consumption of petroleum and emissions in:

- Autos
- SUVs
- Trucks

More Efficient Vehicles + **Increased Use of Alternative Fuels** = **A More Energy Independent Nation**
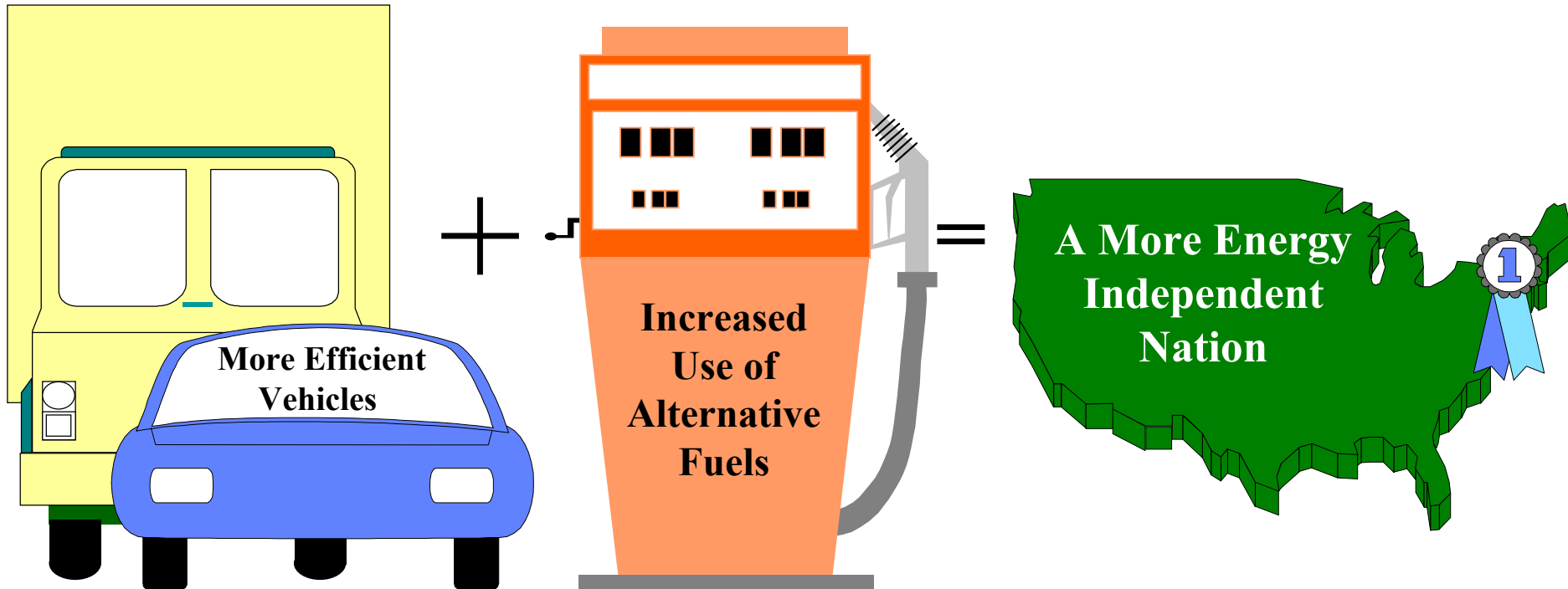
Office of Transportation Technology

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Deputy Assistant Secretary**

**Richard Moorer,
Associate Deputy Assistant Secretary**

**Office of Fuels Development
(John Ferrell)**

**Office of Advanced Automotive Technologies
(Robert Kirk)**

**Office of Heavy Vehicle Technologies
(James J. Eberhardt)**

**Office of Technology Utilization
(David Rodgers)**

Office of Advanced Automotive Technologies

Bob Kirk, Director

PNGV Coordinator (Ed Wall)

Resources Coordinator (Vacant)

Vehicle Systems (Bob Kost)
- Technology Requirements Definition & Validation
- Technology Development
- Lightweight Materials

Energy Conversion (Steve Chalk)
- Fuel Cells
- Piston Engines
- Fuels
- Prop. Sys. Materials

Energy Management (Ray Sutula)
- EV Batteries
- High-Power Energy Storage
- Power Electronics & Electric Machines
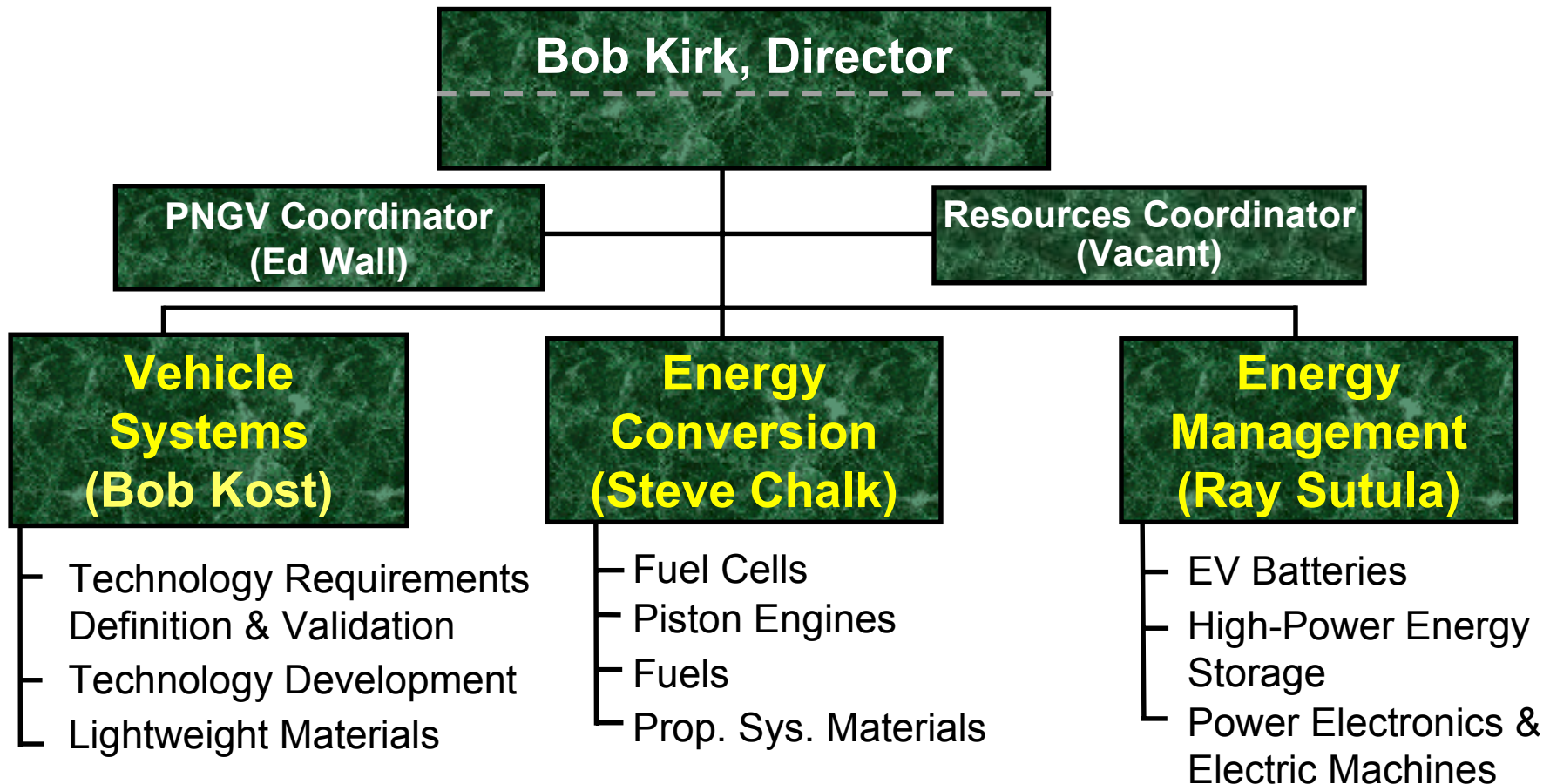
Technology Integration (Cross cut)

OTT/OAAT is Pursuing Broad Range of Advanced Technologies

Energy Conversion

- CIDI
- Fuel Cell
- SIDI
- VCR

Fuels

- Gasoline/Diesel
- Natural Gas
- Hydrogen
- Dimethyl Ether
- Ethanol
- Fischer-Tropsch Fuels

Energy Management

- Batteries
- Flywheels
- Ultracapacitors

Advanced Materials

- Metals
- Composites
- Ceramics

Power Electronics

- Inverters
- Motors
- Generators

Powertrain Configuration

- Parallel Hybrid
- Series Hybrid
- Electric Vehicle
- Conventional

Other Attributes

- Accessory Loads

AAT
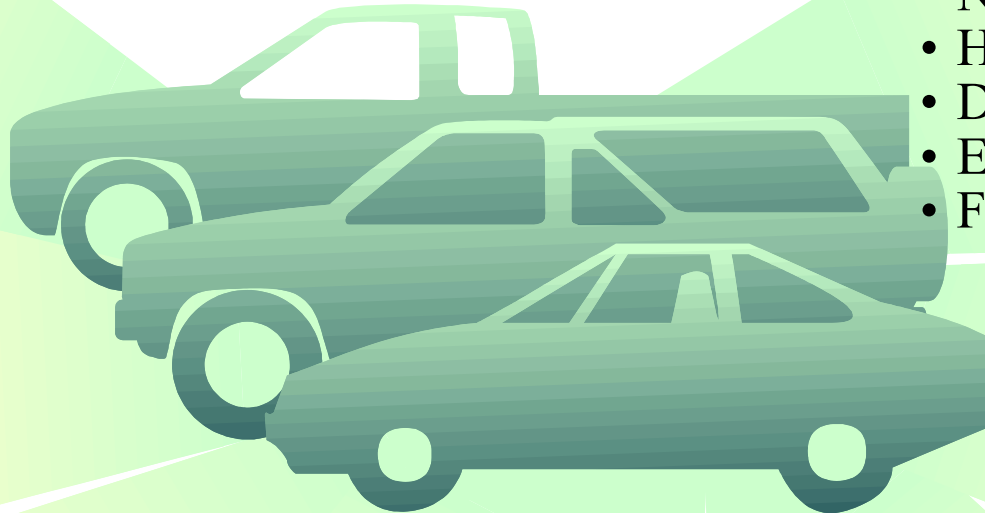
2000 PNGV Concept Vehicles

Ford Prodigy

DaimlerChrysler ESX3

- Lightweight materials reduce vehicle body structure weight 50%*
- Integrated starter/alternator*
- 33% reduction in aerodynamic drag
- Advanced diesel engine with 35% efficiency improvement projected to exceed 70 mpg (gasoline equivalent)*
- High-power battery *

- Body system weighs 46% less*
- Efficient diesel engine, motor, and battery projected at 72 mpg (gasoline equivalent)*
- Cost penalty halved to $7500

GM Precept

- Vehicle body weight reduced 45% *
- World's most energy efficient vehicle lighting system
- Lowest drag coefficient ever recorded for a 5-p sedan
- Dual-axle parallel hybrid achieves 79.6 mpg (gasoline equivalent)

*Government supported technologies

OAAT Strategy
"Systems Driven - Barrier Focused"

Vehicle Systems Driven*

➢ **Derive all technical targets from a Common Vehicle System Perspective**

➢ **Culminate efforts with technology validation at the Vehicle System Level**

Barrier-Focused

➢ **Concentrate available funding on the most critical technical barriers to ensure successful technology development**

(*Most "Bang for The Buck"*)

*R&D Constraints

- **Emissions Control Regulations (projected to be in place when technology is available for the marketplace)**
- **Safety Standards**
- **Attributes of comparable, competitive vehicles (including cost)**

Vehicle Systems Technology Objectives

➢ Set requirements with the help of modeling and analysis

➢ Continue focus on testing component technologies and overall vehicle systems validation through testing and computer modeling

➢ Develop and validate propulsion subsystem technologies and validate OAAT developed technologies that will enable the achievement of 80 mpg in six passenger sedans by 2004

➢ By 2015, Develop and validate automotive propulsion and ancillary subsystem technologies that will enable the achievement of quadrupled fuel economy, near zero regulated and unregulated toxic tailpipe emissions and dramatically-reduced greenhouse gas emissions in family sedans operation on fuels that can be produced from available domestic feed stocks, including those that are renewable

Methodology for Managing Vehicle Systems Consists of Three Integrated Activities

Systems Modeling & Analysis

Digital FunctionalVehicle

Advanced Powertrain Test Facility

Digital FunctionalVehicle

- *Allows rapid layout to view problems and opportunities*
- *Helps OEM suppliers to become better prepared for system level designs*
- *Fewer design iterations & faster convergence on solution*
- *Ties together many different component projects in systems context for minimum energy and emissions*
- *Gives 1st Order Vehicle Designs & "package able" products*

Systems Modeling & Analysis

- *Guide/Prioritize Future R&D*
- *Sets Requirements & Targets*
- *Predicts Performance (F.E. Emissions, Transient, etc.)*
- *Control Strategy Development*
- *Component & Subsystem Model Development*
- *Test Procedure Development*
- *Vehicle Models (SUV, Lt Truck, HD, Auto)*
- *Optimization Techniques*
- *Evaluate new Concepts*
- *Parametric Studies*

Advanced Powertrain Test Facility

- *Model Validation*
- *Validation of Component & Subsystem Technologies*
- *Benchmark technologies & vehicles worldwide*
- *Component, Engine & Vehicle Characterizations*
- *Hardware-in-the-loop*
- *Controls Strategy Development for improved efficiency & lower emissions*
- *Integration Tech. Development*
- *Test Procedure Development*

Government/Industry Partnership under PNGV
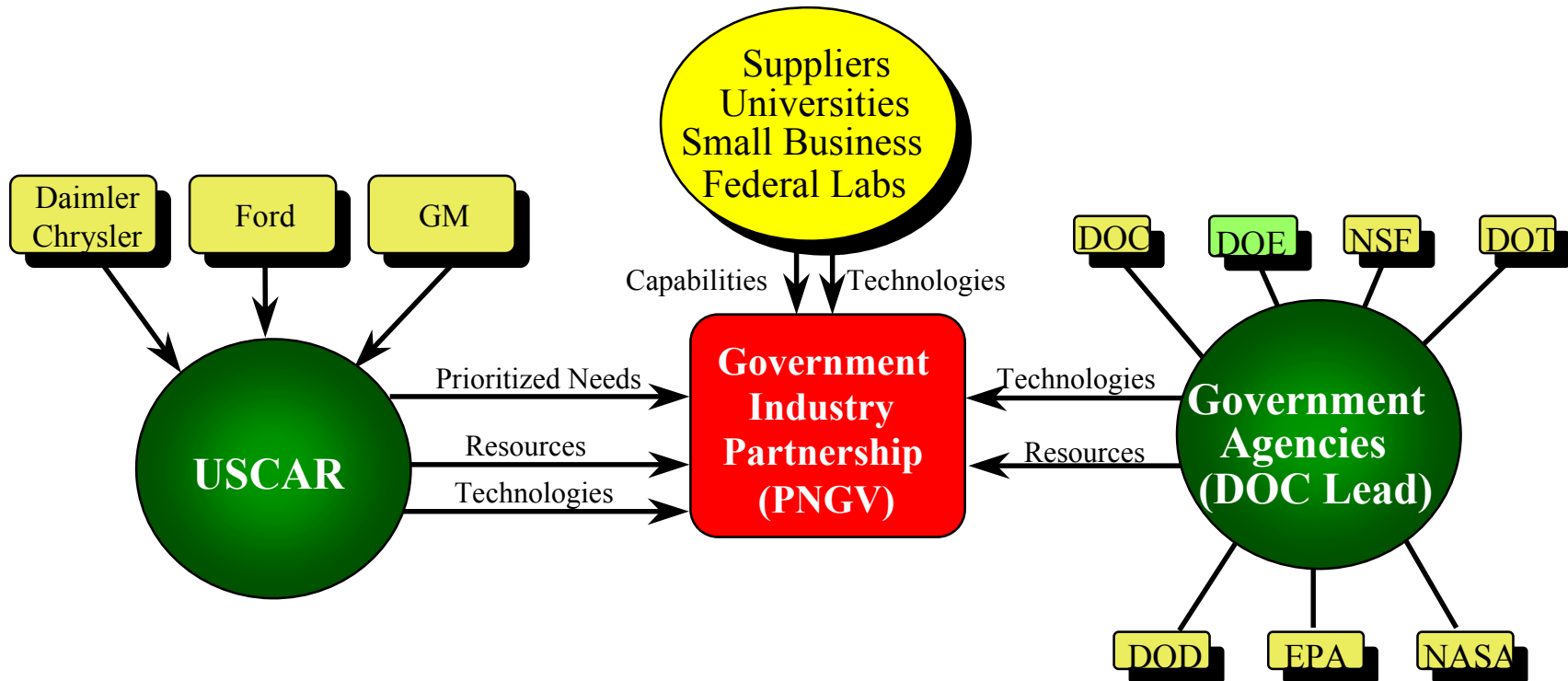
Why OAAT needs both ADVISOR & PSAT?

➢ ADVISOR, developed by NREL and available publicly, has gained worldwide acceptance and has been downloaded by over 3,000 users. This tool is being used to conduct vehicle systems trade-off analyses and to optimize fuel economy and minimize emissions.

➢ PSAT, improved by ANL, is a flexible "forward looking" vehicle simulation model. Its architecture allows powertrain designers to develop realistic control strategies to optimize fuel economy and minimize emissions as well as conduct hardware-in-the-loop testing to evaluate component behavior and validate control strategies in a system environment.

Modeling Development Focus

➢ Continue Development and Validation of Tools and Processes for Systems Integration and Optimization

➢ Provide Tools for Automotive Suppliers and University Competition

➢ Continue Engine Emission and After-treatment Development, and Controls Development

Vehicle Control Strategy Design and Evaluation Using Modeling Tools

Fuzzy Logic Control for Parallel Hybrid Vehicles Using PSAT

Niels Schouten, Oakland University

Development and Use of a Series Hybrid Vehicle Control Strategy for the ADVISOR Simulation Tool

G. Steinmaurer and L. del Re,
Johannes Kepler University Linz, Austria

Presentation
Paper

Fuzzy Torque Distribution Control For A Parallel-Hybrid Electric Vehicle

Reza Langari and Jong-Seob Won, Texas A&M University

Presentation
Paper

Oakland University
Electrical and Systems Engineering
Department

Fuzzy Logic Control for Parallel Hybrid Vehicles Using PSAT

Niels Schouten

Research Associate

Oakland University

2001 Joint PSAT/Advisor Conference, August 28, 2001

Outline

1. Control Objectives

2. Energy Management Strategy

3. Fuzzy Logic Controller

4. Simulation Results

5. Future Work

Control Objectives

- Design a fuzzy logic controller that optimizes the efficiency of the Argonne HIL setup (do not only focus on combustion engine)

- Include possibility to specify trade-off between optimizing fuel economy and minimizing emissions

Argonne HIL Setup
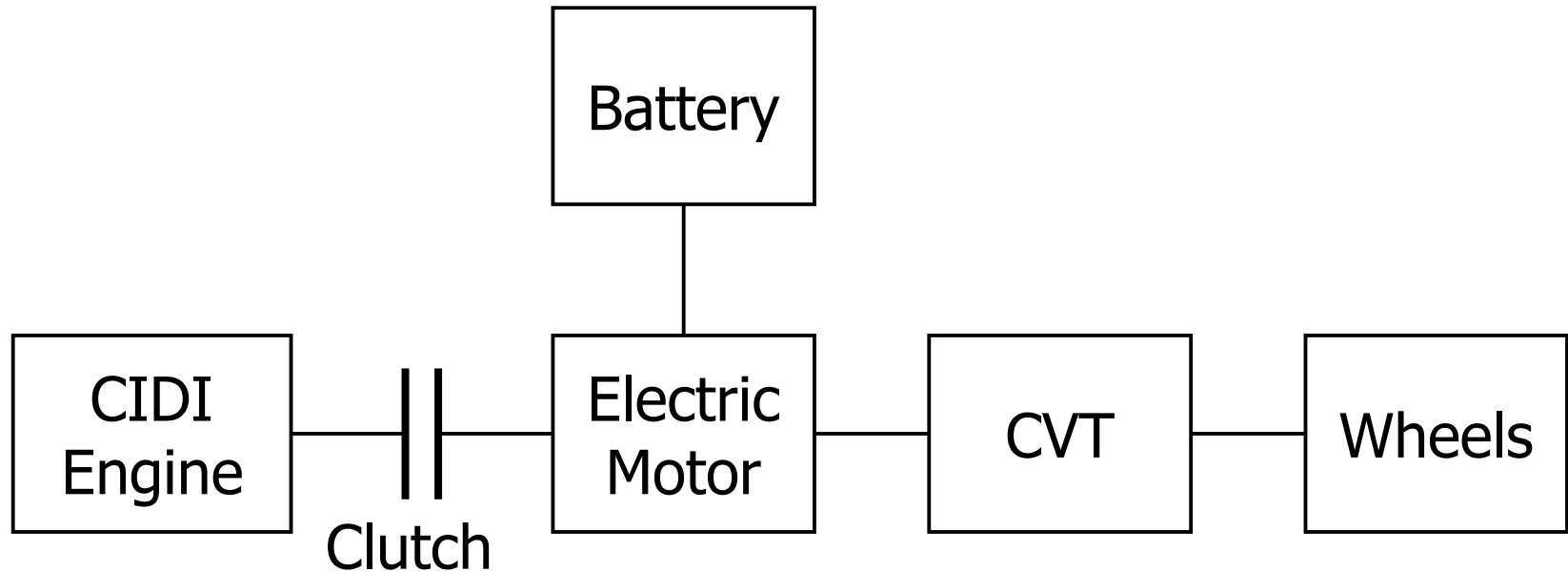
- Parallel configuration with electric motor upstream of transmission (CVT)

Why Fuzzy Logic Control (FLC)?

- Nonlinear

- Flexible, basically any strategy can be implemented using FLC

- Through design iterations it is possible to outperform basically any control method, because strong points of the other method can be incorporated in FLC

- Result is basically multi-dimensional look-up-table / map based control

Controller Overview

Driver Input [-1, 1] →

SOC [0,1] →

EM Speed →

Gear Ratio →

Vehicle Speed →

Fuzzy Logic Controller

→ ICE Command [0, 1]

→ EM Command [-1, 1]

→ ICE Speed

→ Friction Braking [0, 1]
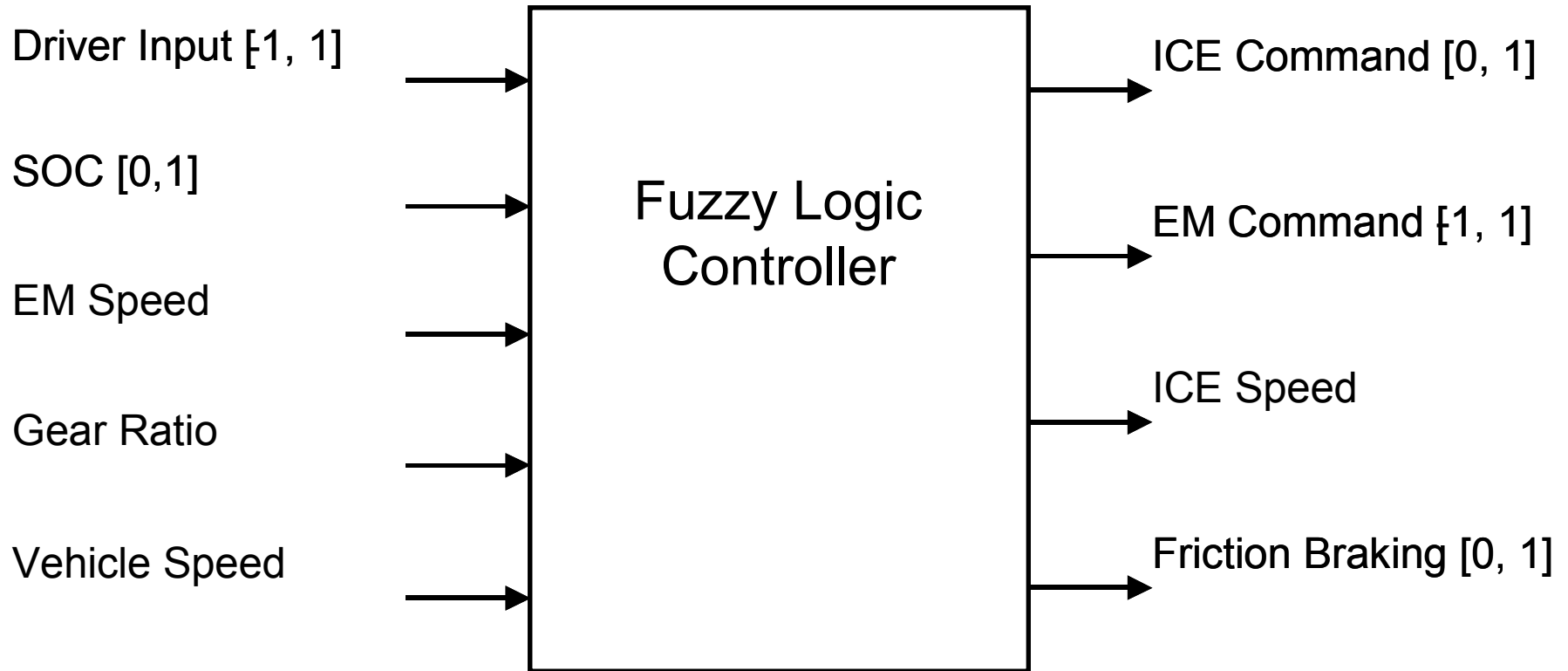
Energy Management Strategy

- Use efficiency / emissions maps to analyze components

- Define optimum regions / lines in maps
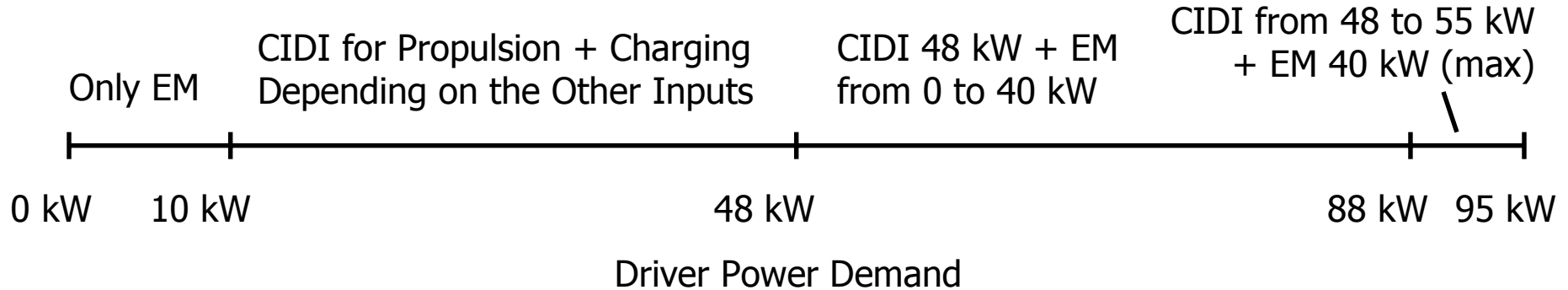
- Design fuzzy logic controller that shifts operating points to optimum regions

Power Split Strategy

Only EM	CIDI for Propulsion + Charging Depending on the Other Inputs	CIDI 48 kW + EM from 0 to 40 kW	CIDI from 48 to 55 kW + EM 40 kW (max)

0 kW   10 kW   48 kW   88 kW   95 kW
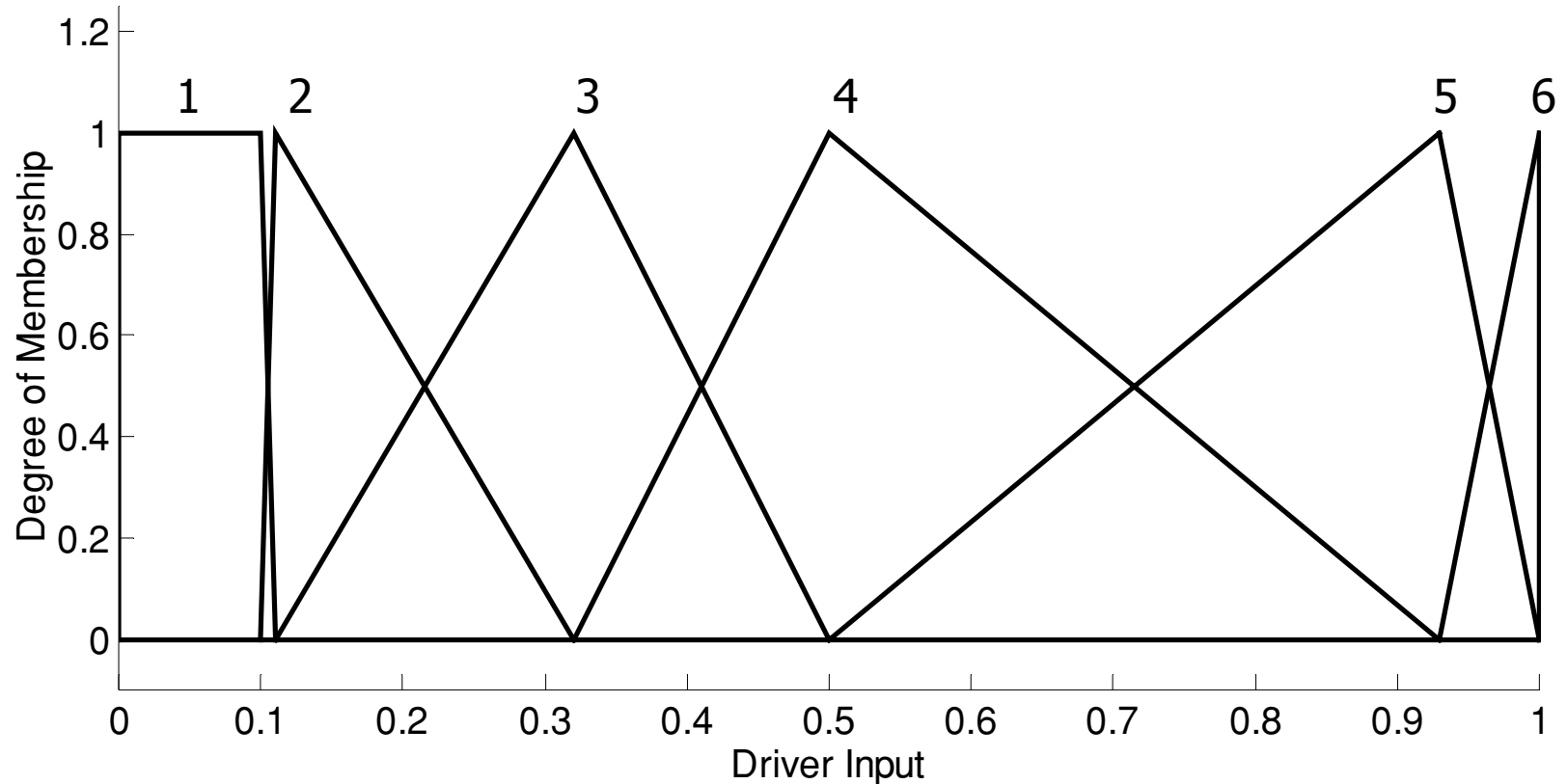
Driver Power Demand

- Power Split of total available power: Electric Motor (EM) + Compression Ignition Direct Injection (CIDI) Engine

- Max CIDI power: 55 kW
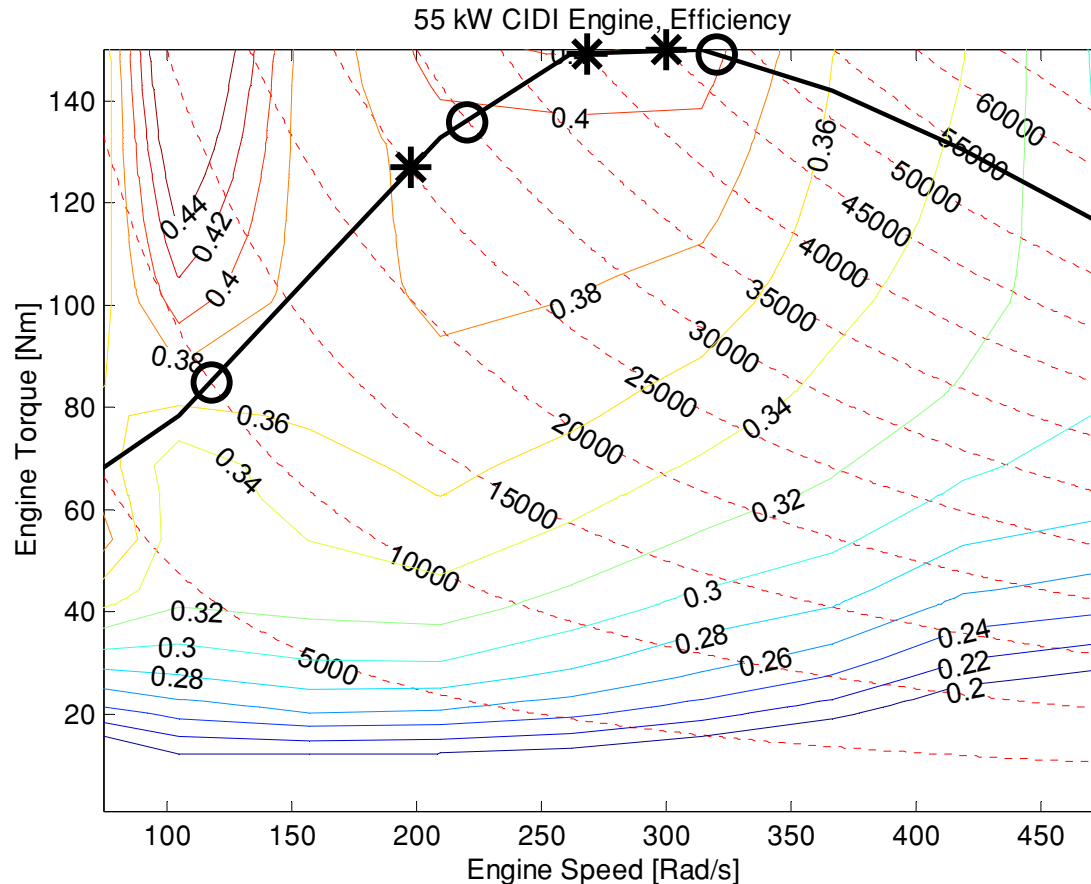 Max EM power: 40 kW

Fuzzy Logic Control

- Strategy implemented as a Takagi/Sugeno controller with the Matlab Fuzzy Logic Toolbox

- Membership Functions only defined for inputs, outputs are normal numbers

Results in linearized torque at the wheels

# Corresponding Outputs for ICE

55 kW CIDI Engine, Efficiency

Stars (*) added to account for charging.

Tuning of Outputs for ICE

- Position of outputs for ICE in engine map can be changed, to tune ICE efficiency and emissions

- Tuning by only moving outputs along lines with equal power ensures that response of vehicle does not change

- Final controller output is obtained through fuzzy interpolation between the output pairs

- This way fuel economy can be optimized for a given level of emissions (ULEV, etc)

Tune Outputs for Reduced NOx

55 kW CIDI Engine, NO$_x$ Emissions [kg/kg of Fuel]
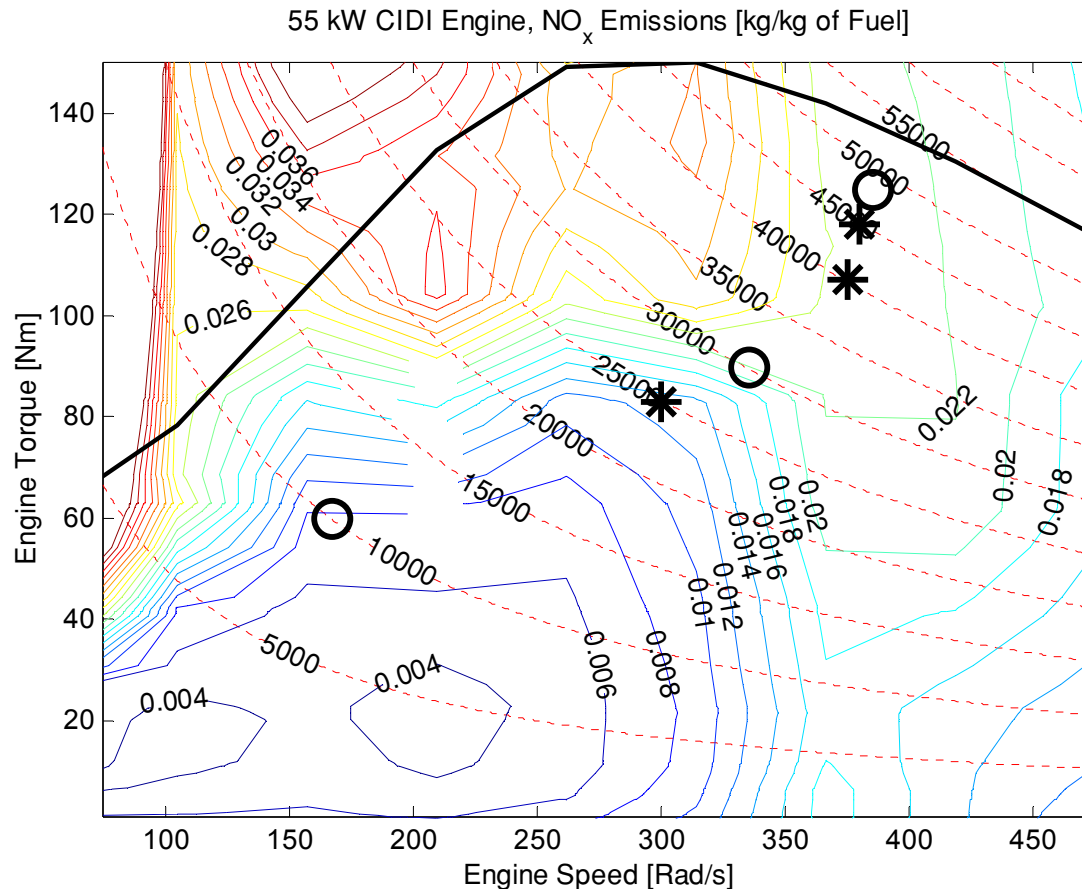
Reduces NOx, but limits efficiency decrease
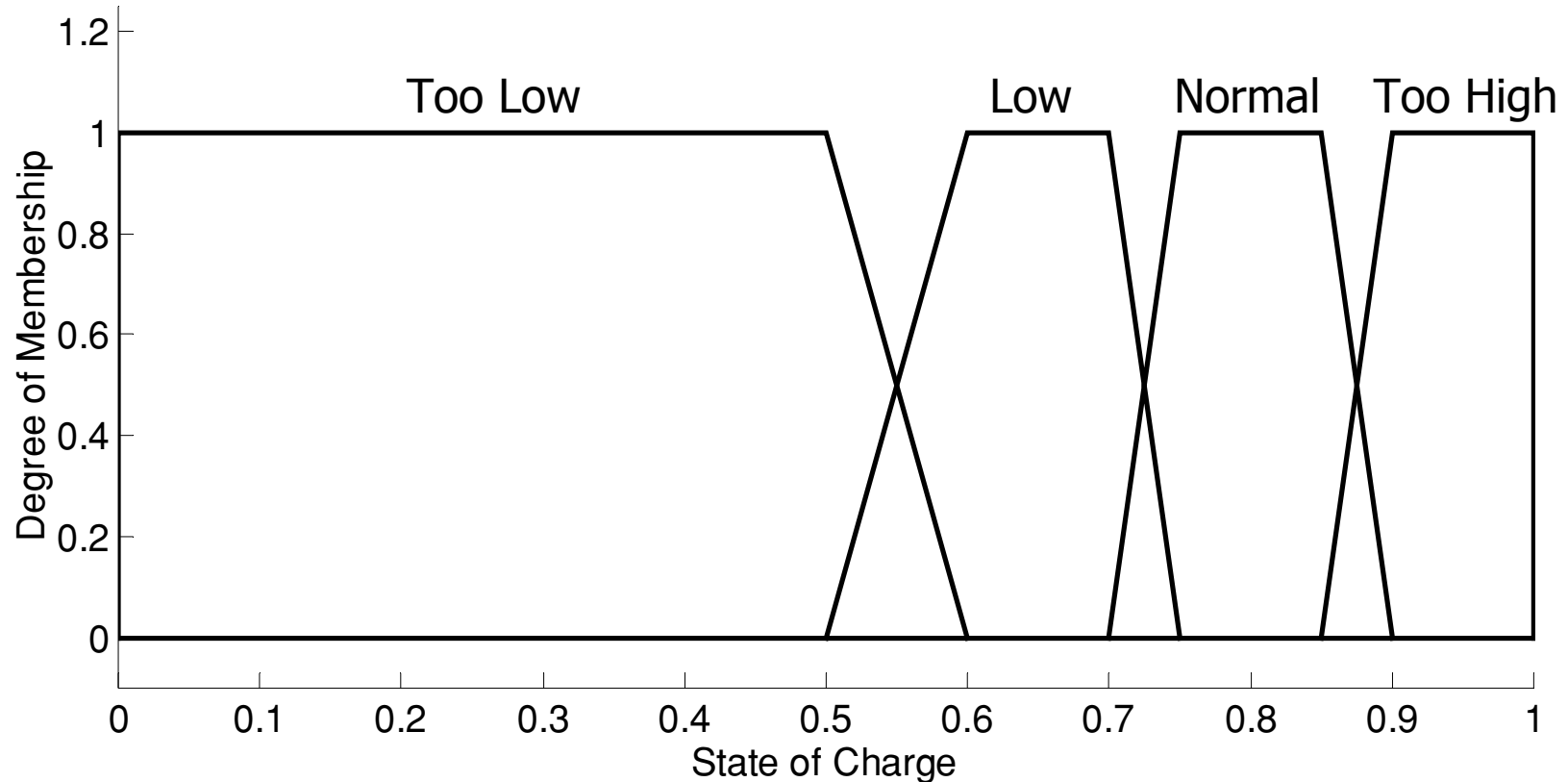
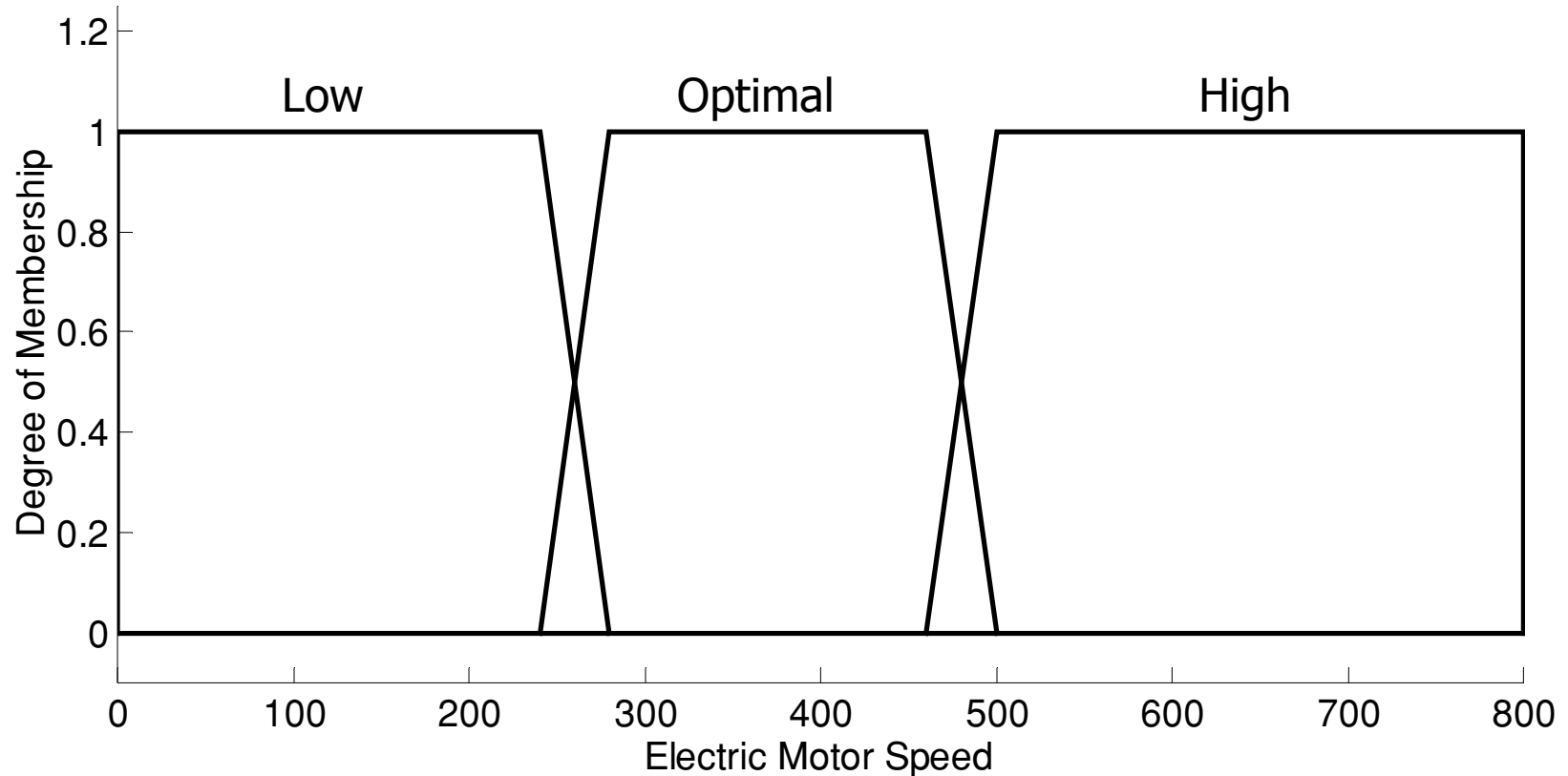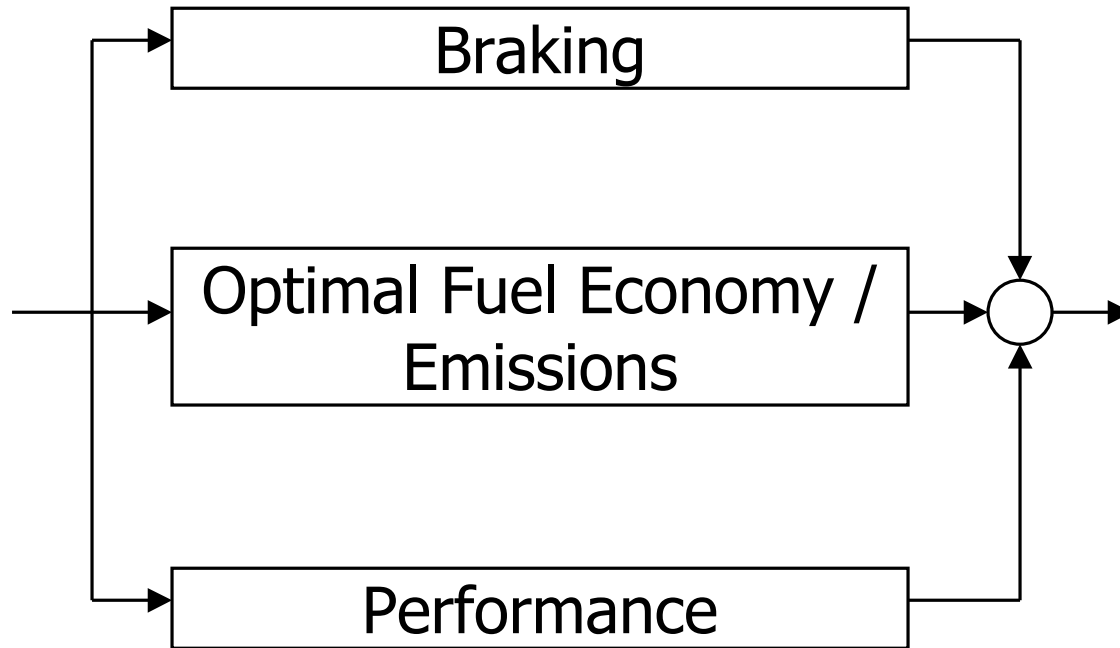If State of Charge is normal, only use electric motor as generator when conditions are optimal

MFs Electric Motor Speed

Preferably only use electric motor as generator when speed is optimal

Rule Base Split Up

```
        ┌──────────────────────────┐
   ┌───→│        Braking           │───┐
   │    └──────────────────────────┘   │
   │                                   │
   │    ┌──────────────────────────┐   ↓
──→├───→│ Optimal Fuel Economy /   │──→ ○ ──→
   │    │      Emissions           │   ↑
   │    └──────────────────────────┘   │
   │                                   │
   │    ┌──────────────────────────┐   │
   └───→│      Performance         │───┘
        └──────────────────────────┘
```

Rule base split up, easier for tuning and changing. Total 44 rules.

If driver input demand is medium *and*

SOC is normal *and*

EM speed is optimal *and*

CVT gear ratio is not the largest *and*

vehicle speed is not low

Then ICE speed is 375 rad/s *and*

ICE command is 0.76 *and*

EM command is −0.25

Reduction of Rules

- Number of rules reduced as much as possible to provide for easier tuning and changing of controller

- Reduction through carefully choosing inputs and outputs and through combining rules

- Optimal Fuel Economy rule base requires 6*4*3*2*3 = 432 rules to cover input space, but has been reduced to 29 rules

Combining Rules

- Example:

    If driver input demand is low *and*

      SOC is too low

    Then ……

- Rule is valid independent of values of the other 3 inputs, therefore combines 3*2*3 = 18 rules

Results Fuel Economy Control

- Highway Cycle (FHDS) 89.3 mpg, 6.7 % better than default PSAT controller

- Urban Cycle (FUDS) 81.0 mpg, 14.9 % better than default PSAT controller

Results Fuel Economy Control

- Losses are smaller in downstream components, which in turn decreases losses in upstream components

- Losses smaller because of smaller charging and discharging power, at better EM speed

- Drag, rolling resistance and tracking error are the same for FLC and default controller, which shows that differences are not caused by deviations from the cycles

Results Reduced NOx Control

- Highway Cycle (FHDS) 23 % less NOx than default PSAT controller, fuel economy −7.0%

- Urban Cycle (FUDS) 28 % less than default PSAT controller, fuel economy −6.1 %

Future Work

- Do more research on the use of neural networks to fine-tune the controller, in case of component wear and variability

- Use global optimization algorithms to optimize controller (see University of Michigan presentation for algorithms)

- Modify the controller to work with fuel cell powered vehicles

Oakland University
Electrical and Systems Engineering Department

Questions

?

Development and use of a

series hybrid vehicle control strategy

for the ADVISOR simulation tool

G. Steinmaurer, L. del Re
University Linz, Austria

- **Combustion engine and the generator**

Best possible efficiency for
each output power
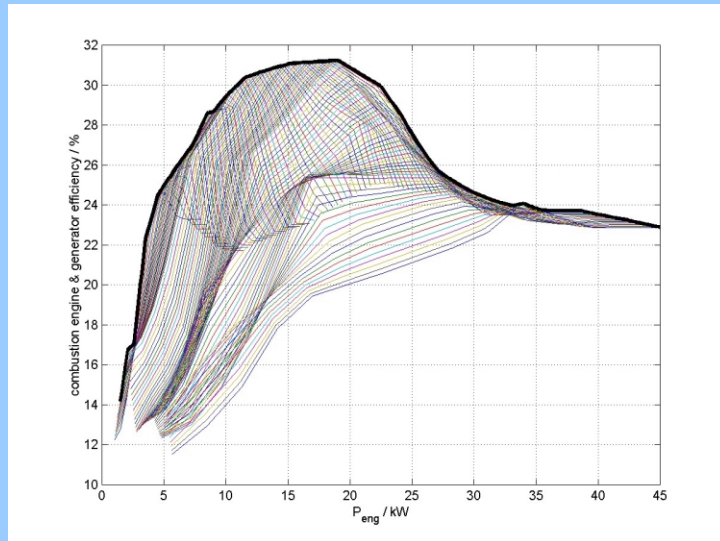
Optimal torque and speed to reach
best efficiency

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Department of Mechatronics

Development and use of a series hybrid vehicle
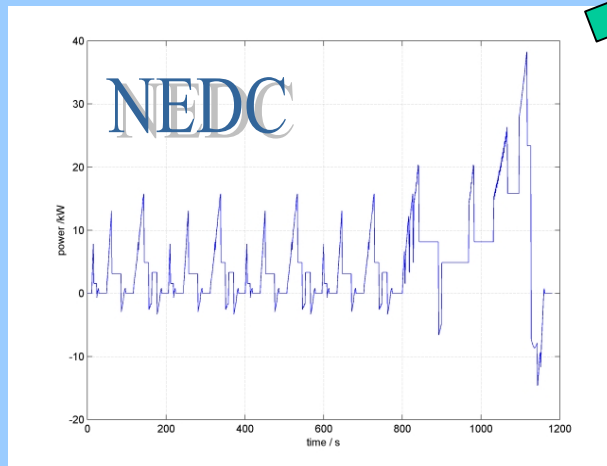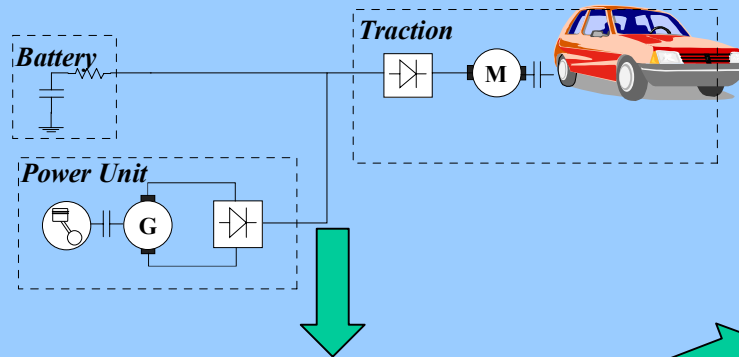control strategy for the ADVISOR simulation tool

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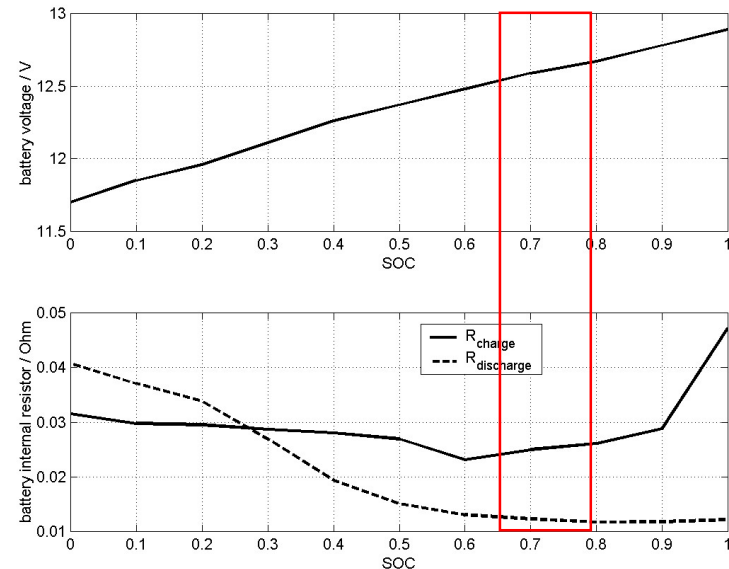
2 sources: engine and battery

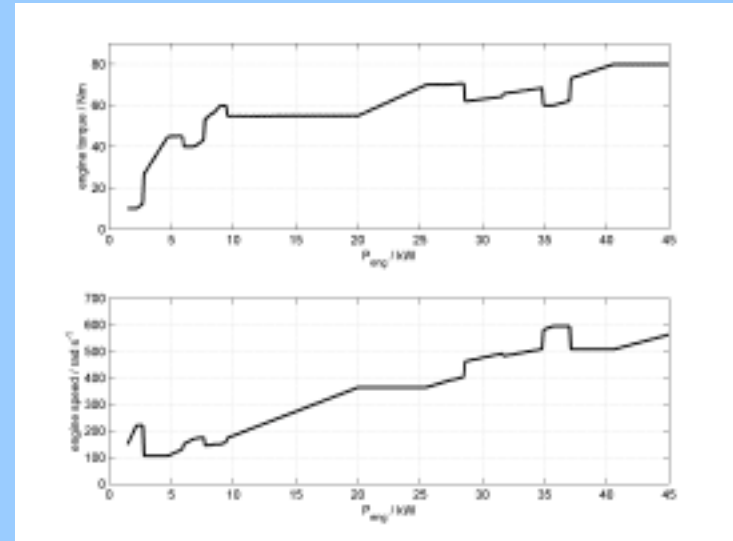$$P_{Trac,j} = P_{eng,j} + P_{Bat,j}$$

$$P_{Trac,j} = P_{eng,j} + I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{bat,j}),$$

Contribution of the combustion engine

$$P_{eng,j} = P_{Trac,j} - I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{Bat,j})$$

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Objective function

Engine fuel power for constant traction power

$$B_j = \frac{P_{eng,j}}{\eta(P_{eng,j})} =$$

$$\frac{P_{Trac,j} - I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{Bat,j})}{\eta(P_{Trac,j} - I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{Bat,j}))}$$

Approximation

$$B_{j,appr} = b_{0,j} + b_{1,j}I_{Bat,j} + b_{2,j}I_{Bat,j}^{2}$$
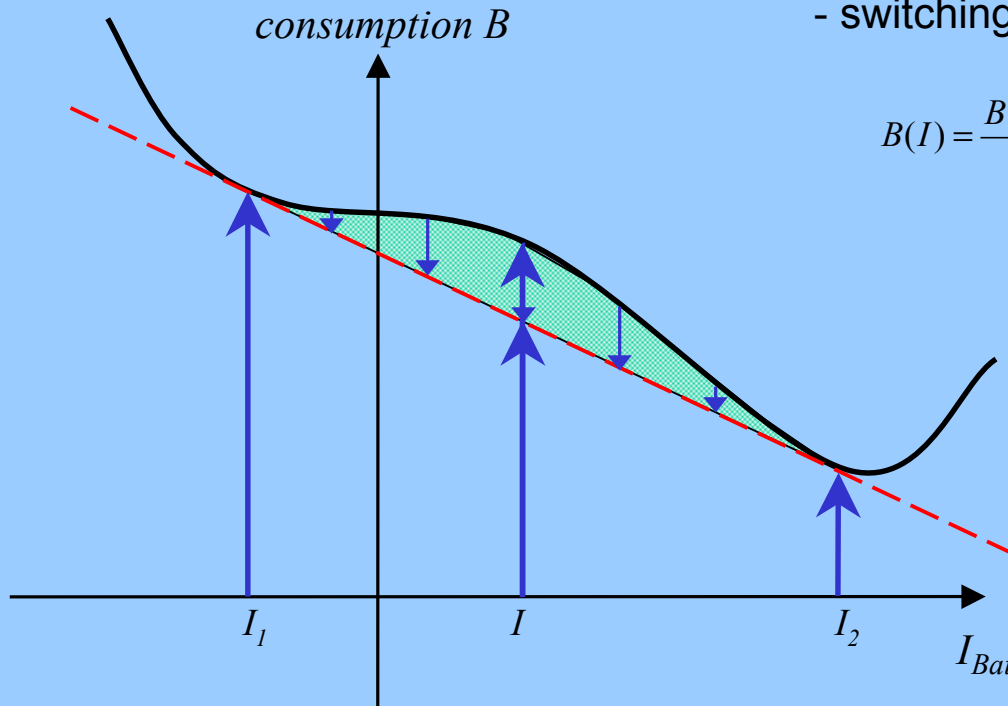

Example of P_{Trac}=20kW

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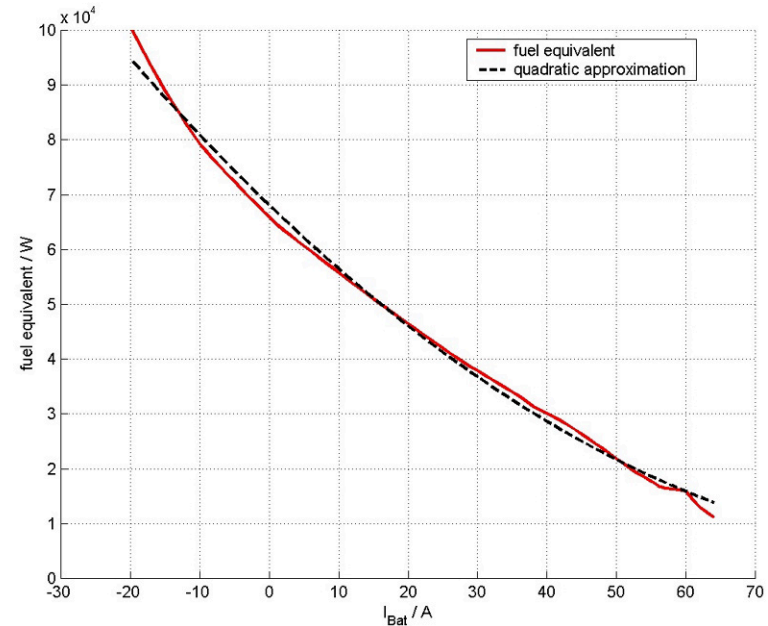
Objective function

consumption B

- switching for non-convex function

$$B(I) = \frac{B(I_2) - B(I_1)}{I_2 - I_1}(I - I_1) + B(I_1)$$

I_1

I

I_2

I_{Bat}

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Objective function

Example of $P_{trac}=20kW$ and engine shoot-down
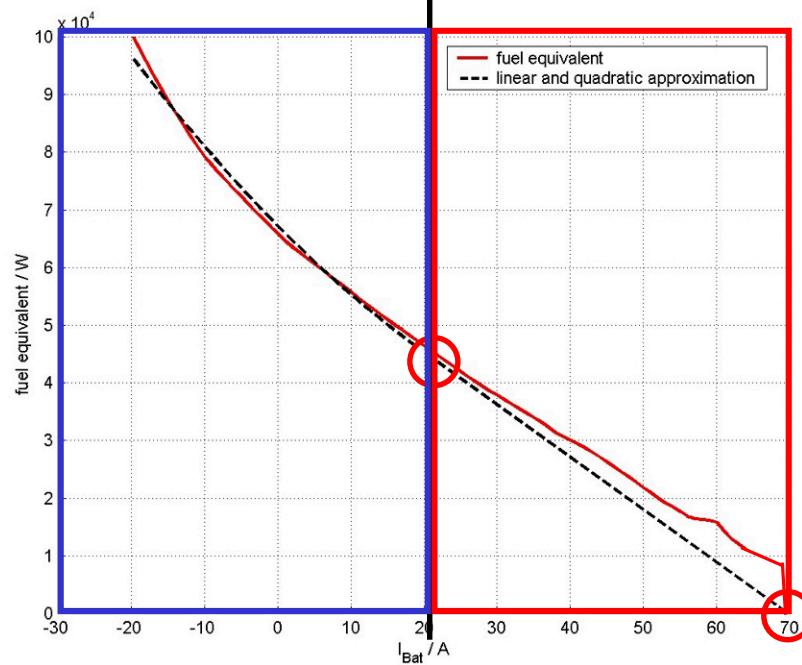
Consumption between 20A and 70A
can not be reached with a
single operation point, but with
switching between two points

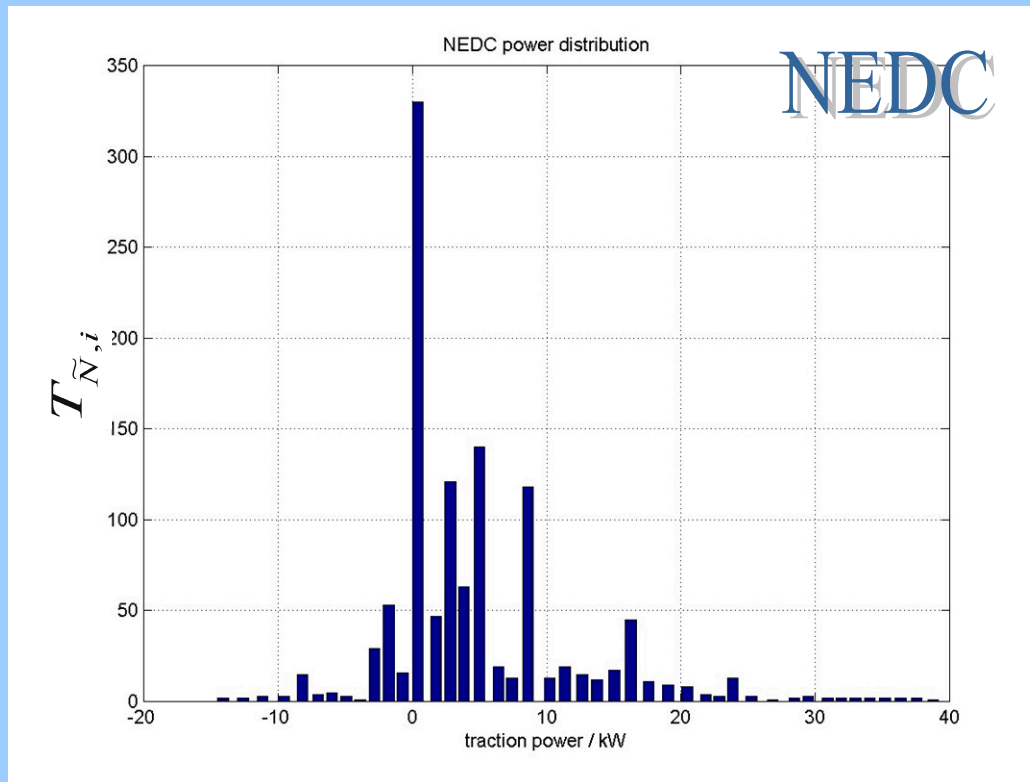Subdividing of the cost function in

- **a linear part**

- **a quadratic part**

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Objective function

Traction power distribution

$\widetilde{N}$ equidistant sectors

Time within i[th] sector

$$T_{\widetilde{N},i}$$

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Optimization task

$$\min_{I_{Bat}} B = \min_{I_{Bat}} \sum_{i=1}^{\tilde{N}} T_{\tilde{N},i} \tilde{B}_i$$

constraint
$$\Delta SOC = SOC(NT) - SOC(0) =$$
$$= T_{cyc} I_{equ} = \sum_{i=1}^{\tilde{N}} T_{\tilde{N},i} I_{Bat,i}$$

Consideration of coulombic efficiency

• Add a nonlinear constraint to the optimization task

• Change the value of the linear constraint to
$I_{equ} T_{cyc}$ <0
and adjusting this value

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Optimization task

$$\min_{I_{Bat}} B \approx \min_{I_{Bat}} \; \frac{1}{2} I_{Bat}^T \mathbf{H} I_{Bat} + f^T I_{Bat},$$

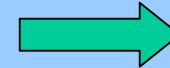$$s.t. \quad \sum_{i=1}^{\tilde{N}} T_{\tilde{N},i} I_{Bat,i} = T_{cyc} I_{equ}$$

$$and \quad I_{Bat}^{Lbound} \le I_{Bat} \le I_{Bat}^{Ubound};$$

$$\mathbf{H} \in R^{2\tilde{N}x2\tilde{N}}$$

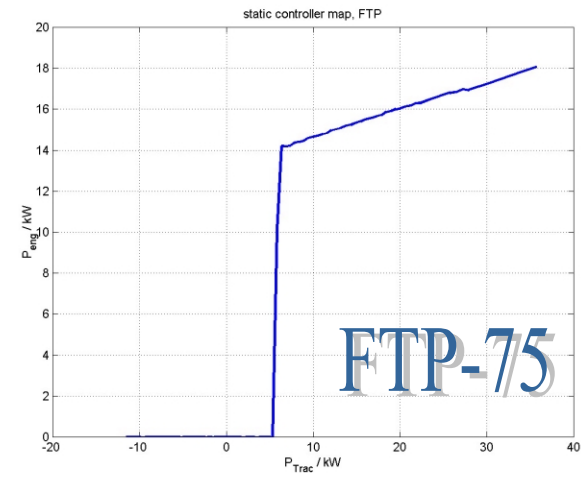$$I_{Bat} \in R^{2\tilde{N}x1}$$
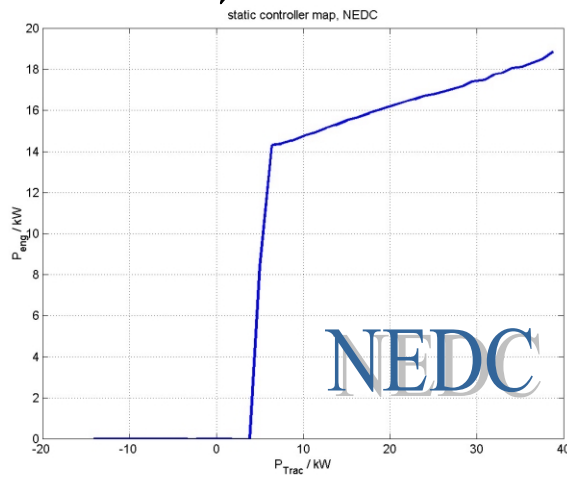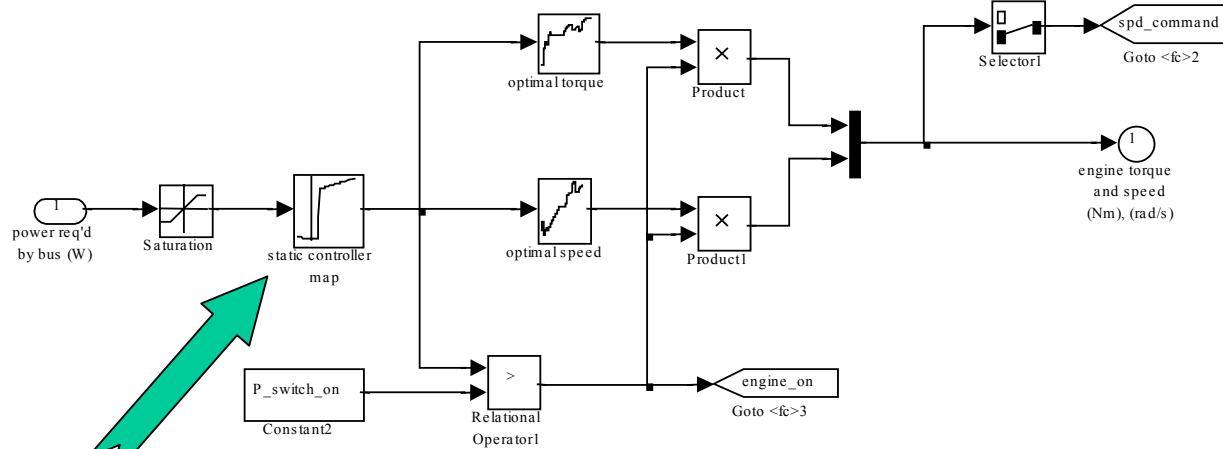
$$f^T \in R^{1x2\tilde{N}}$$

$$I_{Bat,i}(P_{Trac,i}) \quad \Longrightarrow \quad P_{eng,i}(P_{Trac,i})$$

controller

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Simulation results

static controller map, NEDC

NEDC

static controller map, FTP

FTP-75

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Simulation results

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Simulation results

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Conclusion

- **Static, very simple controller structure, based on statistical data**

- **Change of SOC is a tunable factor**

- **The proposed controller is always better than the previous controllers**
  5% - 13%: NEDC
  4% - 10%: FTP-75

- **Controller design based on approximated model and systematic approach yields better results than emiprically tuned controllers**

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- **Finding a trade-off between fuel minimization and engine on/off frequency.**

- **Extend the controller design procedure to parallel type hybrid vehicles.**

- **Draw attention to emission reduction.**

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Development and use of a series hybrid vehicle control strategy for the ADVISOR simulation tool

G. Steinmaurer and L. del Re
Johannes Kepler University Linz, Austria

Department of automatic control and electrical drives

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ABSTRACT

Hybrid vehicles can request the necessary power for driving different speed cycles from more than one power source. The combinations of 2 sources offers new possibilities to minimize the fuel consumption of the combustion engine. This paper discusses a systematic optimization strategy for general series hybrid vehicles in combination with a battery. This approach differs fundamentally from other controllers, which are tuned empirically or using little system information. The proposed control strategy is based on the minimization of a objective function, including the combined losses of the combustion engine and the battery. The minimization procedure yields a static controller map, which guarantees both minimal fuel consumption and a balanced state of charge (SOC) of the battery. Simulations and comparisons to other control strategies, with the hybrid vehicle simulation tool ADVISOR conclude the paper.

INTRODUCTION

Hybrid vehicles are vehicles able to derive power from two alternative sources with essentially different characteristics. Exploiting the corresponding combination possibilities opens new optimization potentials. The standard target of a vehicle control system is the minimization of some cost functions, like the consumption under some constraints. These constraints are typically the charge level of the battery. In most cases, this controller design problem is not solved in terms of optimality control but empirically.

The hybrid vehicle simulation tool ADVISOR allows to test different control strategies close to reality way.

There exists an enormous number of proposals for the energy management of series hybrid vehicles. These controllers range usually between the two extreme strategies of constant power and load following. Also the energy management systems, which are used to control series hybrid vehicles within ADVISOR, are based on one of these to two different strategies.

In other applications the optimal strategy requires some compromise between this two strategies[1],[2], the choice is usually following some kind of physical reasoning. While the optimization for a static operating point is in general not a problem, the consideration of dynamic trade-off is much more complex. Therefore, predictive approaches as in [3] have been proposed, usually based on some kind of pattern recognition. Other proposals, e.g. [4] include a rule-based control and energy management, some are based on a fixed static controller map [5], others using fuzzy logic[6].

An important topic in the case of hybrid vehicles is the consideration of changes in the charge level of the battery during the cycle. Previous control strategies for series hybrid vehicles in the software tool ADVISOR are not able to predict the SOC-level before running a drive-cycle. To yield a desired SOC-value, these control strategies are simulating several runs with different parameters and comparing the SOC-level at the end of a cycle with the desired value and take the controller with the best SOC-fitting.

Instead, the proposed control strategy is able to design a controller based on the knowledge of statistical data (distribution of required traction power to drive a cycle) as usually known in the automotive industry. This controller minimizes the fuel consumption of the combustion engine and the desired SOC-level at the end of a cycle is reached within some uncertainty.

The paper is organized as follows: after stating the general problem we will discuss the fuel consumption of the combustion engine depending on the contribution of the battery. Then we are using this knowledge to define an optimization task under the constraint of a balanced SOC-level. The optimization task results in a static controller map for each driving cycle. These controllers will be tested and compared to controllers of ADVISOR. Conclusions and outlook comments close the paper.

PROBLEM STATEMENT

The goal of a control strategy of a (series) hybrid vehicle is always the minimization of some costs, e.g. consumption and/or emissions. In comparison to

emissions the fuel consumption can be calculated with higher degree of accuracy by using static maps (speed and torque vs. BSFC) and neglecting dynamic effects. In the case of emissions, dynamic behavior plays a more important role.

Further data and parameters are taken from ADVISOR 3.1, where the 'default_series_in' has been loaded.

One main advantage of a series hybrid vehicle is the possibility to operate the engine always in its best efficiency region to deliver a specified power. Figure 1 shows the best possible efficiency for every output power of the electrical generator, that means that also the efficiency of the generator is taken into account. P_{eng} is the power, resulting from the combustion engine in combination with the generator.
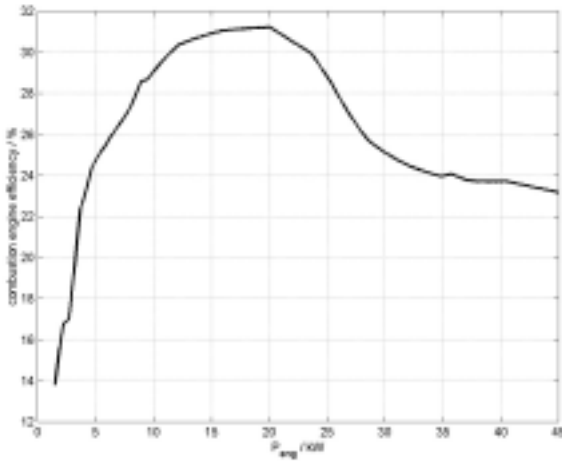
Figure 1: Best efficiency of the engine-generator-electronics over the power span

This best efficiency point can be reached by using the combustion engine as shown in Figure 2.

FORMATION OF A GENERAL COST FUNCTION

The proposed controller design is based on the minimization of an objective function, e.g. the total fuel consumption during one driving cycle. The first step in this design consists of subdividing the time depending total traction requirement $P_{Trac}(t)$. These required traction power depends on the speed profile and on vehicle parameters, like vehicle mass, drag coefficient, etc. $P_{Trac}(t)$ is calculated from ADVISOR and we assume that this time sequence is known for a given cycle.

For any real-time speed profile, the power profile can be computed off-line.
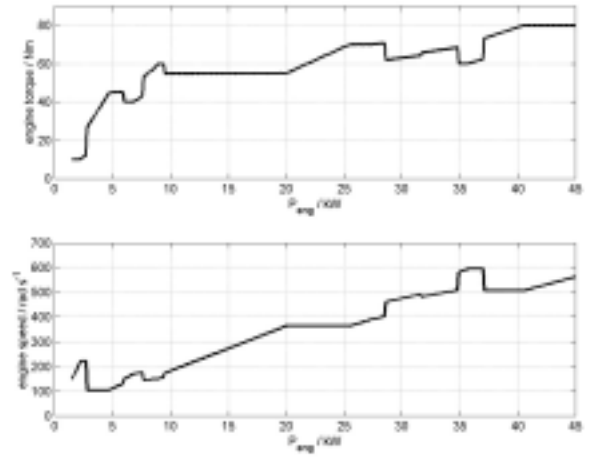
Figure 2: Optimal torque and speed to reach best efficiency

In a first approximation, $P_{Trac}(t)$ is replaced by a discrete sequence $P_{Trac,j}$

$$P_{Trac,j} = P_{Trac}(t)|_{t=jT} \quad , j = 1..N \qquad (1),$$

where T is the sampling period and N is the number of samples. ADVISOR uses a period of 1s.

The traction requirements $P_{trac,j}$ can be delivered by two sources, the combustion engine (including generator) and the battery. Since both sources are supplying at the common series power bus, the overall power is simply the sum of the two sources.

$$P_{Trac,j} = P_{eng,j} + P_{Bat,j}$$
$$P_{Trac,j} = P_{eng,j} + I_{Bat,j}(U_{Bat,j} - I_{Bat,j}R_{bat,j}), \qquad (2)$$

where the contribution of the battery can be described as a voltage source U_{Bat} with an internal resistor R_{Bat}. Equation 2 holds both for charging ($I_{Bat}<0$) and discharging ($I_{Bat}>0$). Usually, the battery voltage and the resistance depend on the state of charge of the battery and on the battery temperature T_{Bat}. Also the different values of the resistor for charging and discharging must be taken into account.

$$R_{Bat} = \begin{cases} R_{dis}(SOC, T_{Bat}) & I_{Bat} > 0 \\ R_{chg}(SOC, T_{Bat}) & I_{Bat} < 0 \end{cases} \qquad (3)$$
$$U_{Bat} = U_{Bat}(SOC, T_{Bat})$$

Typical dependencies on SOC are implemented in ADVISOR and can be seen in figure 3.
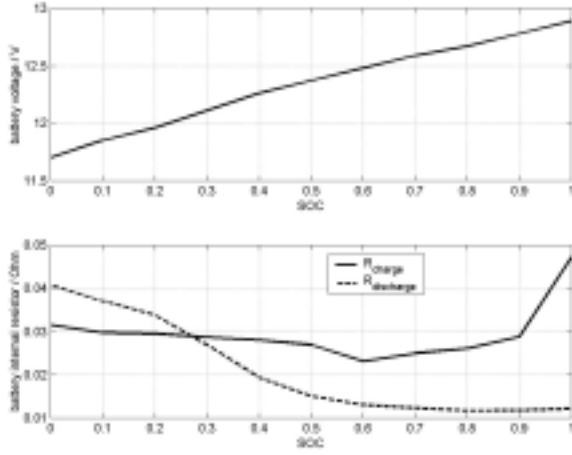
Figure 3: Influence of SOC
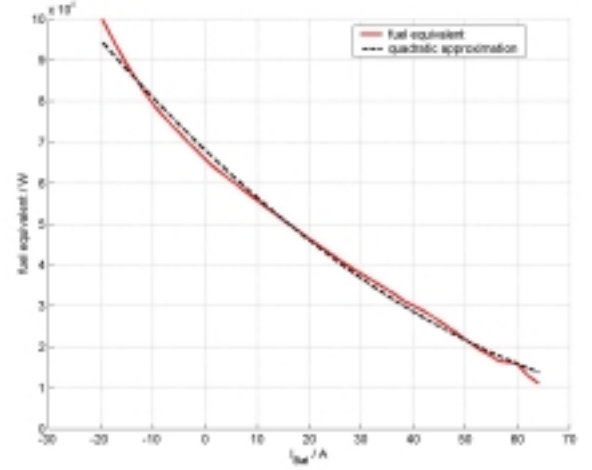
Figure 4: Fuel consumption for P_{Trac}=20kW

Hence we assume a given series hybrid vehicle, driving a predefined cycle, indicating that the traction requirements $P_{Trac,j}$ are known. In this case, the contribution of the combustion engine can be written in terms of the battery current (Figure 4).

$$P_{eng,j} = P_{Trac,j} - I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{Bat,j}) \quad (4)$$

where n_{ess} is the number of battery modules. The engine fuel power, depending on the delivered power and the corresponding efficiency, can then be calculated as

$$B_j = \frac{P_{eng,j}}{\eta(P_{eng,j})} = \frac{P_{Trac,j} - I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{Bat,j})}{\eta(P_{Trac,j} - I_{Bat,j}(n_{ess}U_{Bat,j} - I_{Bat,j}R_{Bat,j}))} \quad (5)$$

For given battery conditions and known traction requirements the fuel consumption is a function of the battery current alone.

Assuming that the traction requirement $P_{Trac,j}$ remains constant, the consumption B_j can be calculated as a function of the battery current, considering the different values for charging and discharging of the internal resistor.

To simplify mathematical computation in the controller design, the cost are approximated in terms of a polynomial of second order

$$B_{j,appr} = b_{0,j} + b_{1,j}I_{Bat,j} + b_{2,j}I_{Bat,j}{}^2 \quad (6)$$

CONSIDERATION OF ENGINE IDLING

Using the description of the fuel consumption for a given P_{Trac} for any battery current does not take into account the possibility of engine switching off, which is one of the main reason of the energy saving potentials of a hybrid vehicle. Whatever, delivering the total needed power from the battery, the engine could be shut down instead of idling and therefore the consumption is zero. This effect can be described by a modified cost function as in figure 5.
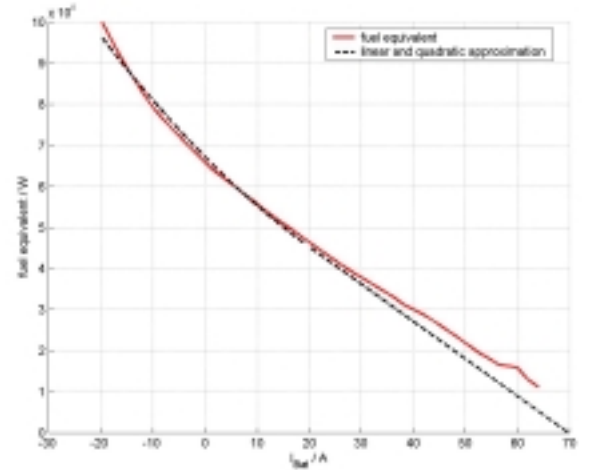
Figure 5: Fuel consumption for P_{Trac}=20kW, engine shut down

In this case, delivering 20kW needs about 70A of battery current and the engine can be shut down. Another important point can be seen in this figure. To supply 20kW with a battery current between 20A and 70A, the approximation of the fuel equivalent shows lower values than the original consumption. This lower value can not be reached with a single operation point, but by the use of 2 operation points (20A and 70A) and switching between them. Further details can be taken from [7].

The cost function for this case consists of a combination of a quadratic interpolation ($I_{Bat} < 20A$) and a linear description (20A..70A).

OBJECTIVE FUNCTION

To build up a general cost function, the range of occurring traction requirements P_{Trac} was subdivided into $\widetilde{N}$ equidistant sectors. The time within one sector is summed up, yielding a power distribution for each cycle (Figure 6). The total time within the i-th sector is denoted as $T_{\widetilde{N},i}$. For each sector a mean cost function $\widetilde{B}_i$, derived from equation 6 is assumed.
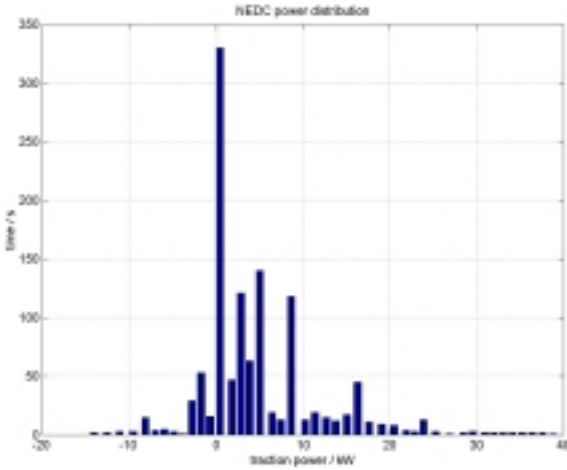
Figure 6: Power distribution of NEDC

Second, the dependence of the battery parameters from temperature and SOC has not been considered in the controller design. So the controller assumes, that the change in the state of charge level of the battery is negligible and the battery is always working in the predefined operation point.

OPTIMIZATION TASK

The next step is the minimization of the fuel consumption of the combustion engine for the overall drive cycle

$$\min_{I_{Bat}} B = \min_{I_{Bat}} \sum_{i=1}^{\widetilde{N}} T_{\widetilde{N},i} \widetilde{B}_i \quad (7)$$

but also having regard to the charge level of the battery. To make the consumption with different hybrid vehicle control strategies comparable, the state of battery charge at the beginning and at the end of a drive cycle have to be equal. To comply with this requirement, an auxiliary condition

$$\sum_{i=1}^{\widetilde{N}} T_{\widetilde{N},i} I_{Bat,i} = T_{cyc} I_{equ} \quad (8),$$

must be added to the optimization problem formulation, where T_{cyc} is the total duration of the cycle. This condition guarantees, that the SOC-level changes during the driving cycle with

$$\Delta SOC = SOC(NT) - SOC(0) = I_{equ} T_{cyc} . \quad (9)$$

The main advantage of this control design structure is that the final SOC-level of the battery can be chosen as a free parameter.

CONSIDERATION OF COULOMBIC EFFICIENCY

The coulombic efficiency η_{coul} tries to describes loss effect during battery-charge. The proposed optimization task with the auxiliary constraint (eq. 8) to guarantee a balanced state of charge is only valid for battery models with a coulombic efficiency of 1. There are two ways to handle (more realistic) values of $\eta_{coul} < 1$

1. Add a nonlinear constraint to the optimization task. This can be done by multiplying negative values (=charging) of the battery current by η_{coul}.

2. Change the value of the linear constraint (eq. 8) with $I_{equ} T_{cyc} < 0$ and adjusting this value to compensate imperfect charging ($I_{Bat} < 0$).

In this paper, the second procedure was implemented in the controller design to remove the effects of non-ideal charging. The first treatment extents the needed computation time to solve the optimization task.

The objective function for each single sector i can be subdivided into a linear and a quadratic part. This optimization procedure results in solving a sequential quadratic optimization problem [8] of order $2\widetilde{N}$.

$$\min_{I_{Bat}} B \approx \min_{I_{Bat}} \quad \frac{1}{2} I_{Bat}^T \mathbf{H} I_{Bat} + f^T I_{Bat},$$

$$s.t. \quad \sum_{i=1}^{\widetilde{N}} T_{\widetilde{N},i} I_{Bat,i} = T_{cyc} I_{equ}$$

$$and \quad I_{Bat}^{Lbound} \leq I_{Bat} \leq I_{Bat}^{Ubound};$$

$$\mathbf{H} \in R^{2\widetilde{N} x 2\widetilde{N}}$$

$$I_{Bat} \in R^{2\widetilde{N} x 1}$$

$$f^T \in R^{1 x 2\widetilde{N}}$$

(10)

which can be done using the MATLAB *quadprog*-procedure [9].

Simulation results

ADVISOR IMPLEMENTATION

The proposed control design procedure yields a controller structure, shown in Figure 7.

An important part is the setting of the *engine_on* variable during the simulation to guarantee correct shut-down and power-up of the combustion engine.
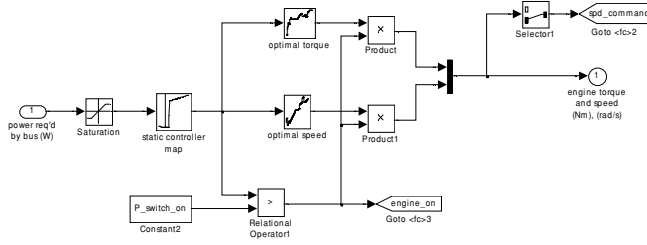

Figure 7: Model of series hybrid vehicle controller strategy

Simulations were done with ADVISOR with several drive cycles, whereby two of them (CYC_NEDC and CYC_FTP) are shown here. The *'default_series_in'* hybrid vehicle configuration has been loaded, the controller were also tested for hot and cold initial conditions to compare the influence on the produced emissions.

NEDC CYCLE

The optimization procedure yields in static controller map (see figure 8 for the NEDC controller). Figure 9 shows the requested power of the combustion engine and the charge history of the battery during the NEDC test cycle. The change of the charge level is within 0.5% of its initial value of 0.7.

FTP-CYCLE

Figure 10 shows the yielding controller map for the FTP-driving cycle. This map is slightly different from the controller for NEDC. This controller also keeps ΔSOC within the desired tolerance of 0.5%.
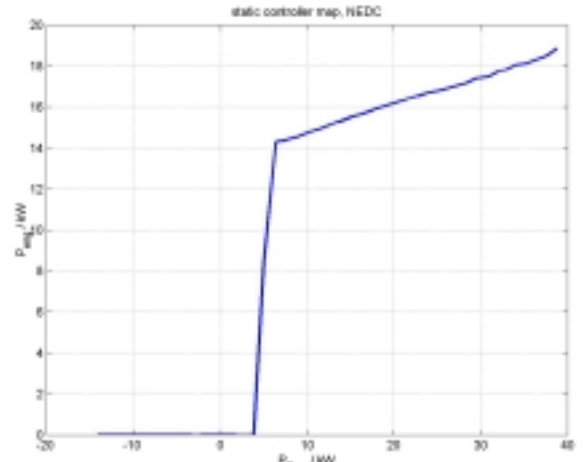
Figure 8: Static controller map for NEDC
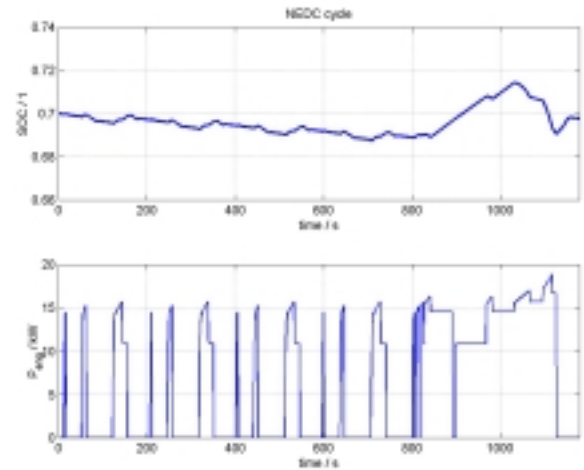
Figure 9: Charge history and P_{eng} during NEDC
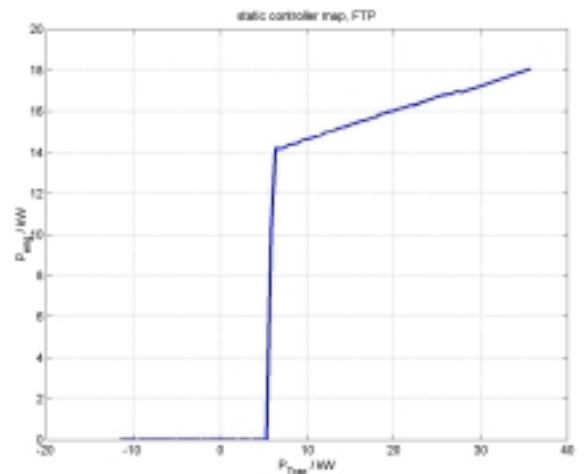
Figure 10: Static controller map for FTP-cycle

To compare the proposed series hybrid controller design to other control strategies, simulations with the same vehicle configuration were done with all built-in controllers. Results can be seen in figure 11, where the consumption in l/100km is compared.
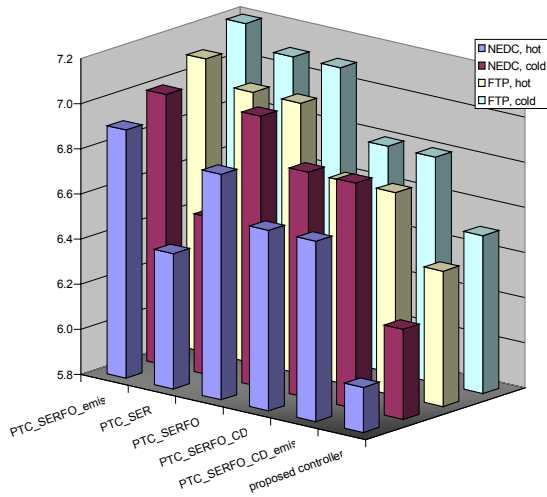
Figure 11: Fuel consumption with different controllers

CONCLUSION AND OUTLOOK

Summarizing, we can conclude that the proposed controller design procedure provides a efficient way to minimize the fuel consumption of a series hybrid vehicle within ADVISOR. Comparing the results, the new controller is always better than the previous built-in controllers for series hybrid vehicles. The reduction of fuel consumption for NEDC ranges from 6% to 13% (cold start) and from 5% to 11% (hot). For the FTP driving cycle the proposed controller yields improvements of 4% to 10% (cold and hot) of the fuel use.

This paper shows that even a controller design based on a simplified model with a systematic approach yields in better results than a controller, which are tuned empirically or system information is only used in a very small extent.

A minimized fuel consumption appears always in combination with a high shut-down and power-on frequency. So the next necessary steps for the control optimization concern in finding a trade-off between a reduction of engine on/off frequency and the fuel minimization or adding additional constraints regarding allowed changing rates for the combustion engine power.

Further this controller design procedure should be extended to parallel type hybrid vehicles. Also attention can be drawn to minimize emission during drive cycles.

CONTACT

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REFERENCES

[1] Norbeck-JM, Barth-MJ, Farrel-JA, Heffel-JW, "Development and avaluation of a hydrogen fuel power plant for a hybrid electric vehicle – phase II", Final Report, South Coast Air Quality Management District, Contract 95073, Project 7, 1997.

[2] Neuendorf-N, Waltermann-P, "Model-based design of operating strategies for hybrid electric vehicles", 32nd ISYTA Conference, Vienna, Austria, June 14-18,1999.

[3] Farrel-JA, Barth-MJ, Heffel-JW, "Hydrogen-powered advanced hybrid-electric vehicles", Final Report for the Mobile Source Air Pollution Review Commitee (MSRC) under the AB2766 Discretionary Fund Work Program 1998.

[4] Jalil-N, Kheir-NA, Salman-M, "A rule-based energy management strategy for a series hybrid vehicle", Proceedings of the 1997 American Control Conference, vol. 1, pp. 689-92, 1997

[5] Bourne-C, Faithfull-P, Quigley-C, "Implementing control of a parallel hybrid vehicle", International Journal of Vehicle Design, vol. 17, pp. 649-62, 1996.

[6] Hyeuon-Dong-Lee, Seung-Ki-Sul, "Fuzzy-logic-based torque control strategy for parallel-type hybrid electric vehicle", IEEE-Transactions on Industrial-Electronics, vol. 45, no4, pp.625-32, 1998

[7] Steinmaurer-G, del Re-L, "Optimal control of dual power sources", to be published at the Conference on Control Applications, CCA 2001, Mexico, September 5-7, 2001

[8] Fletcher-R, "Practical methods of optimization", second edition, John Wiley & Sons, 2000.

[9] MATLAB Optimization Toolbox

Fuzzy Torque Distribution Control Design
for
a Parallel Hybrid Electric Vehicle

Presentation

by

Jong-Seob Won

Texas A&M University
Mechanical Engineering Department

May 10, 2001

Objective

Design a Torque Distribution Control for a parallel hybrid vehicle using Fuzzy Decision Making.

Typical Parallel Hybrid Powertrain

In Parallel Hybrid,

Both the electric motor and the gasoline engine can provide propulsion power.
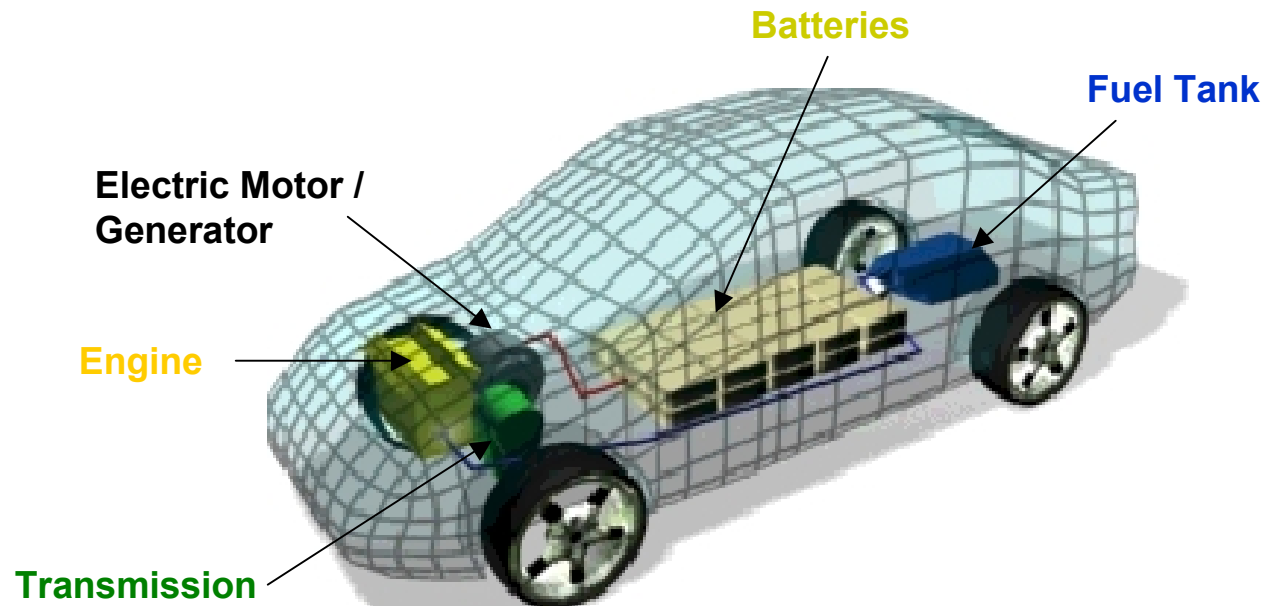
Vehicle Modeling and Torque Relation
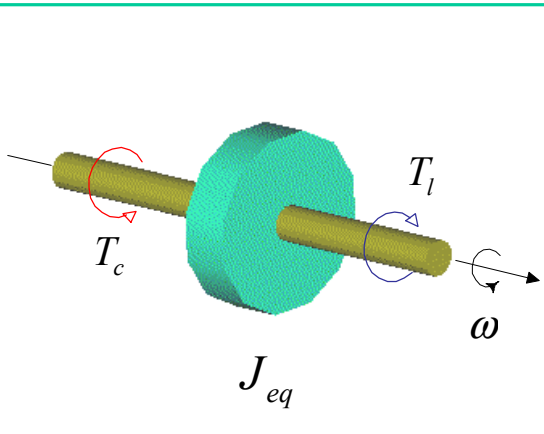
Drive Shaft Model equation:

$$T_c - T_l = J_{eq} \times \frac{d\omega}{dt}$$

J_{eq} : **Equivalent inertia of a vehicle**

where T_c : **Torque command from the driver**

$$T_c = T_{ec} + T_{mc} - T_{bc}$$

T_{ec} : **Engine torque command on the drive shaft**

T_{mc} : **Motor torque command on the drive shaft**

T_{bc} : **Brake torque command on the drive shaft**

T_l : **Road load torque**

T_{DC} : **Torque required for acceleration or deceleration**

$$T_{DC} = T_c - T_l$$

T_l

T_c

ω

J_{eq}

* Powertrain component models are taken from Buntin's thesis [1994].

Control Design for Energy Management in Parallel HEV

Objective of the control design in Parallel HEV is

To distribute the torque demand into two power sources (engine and motor), while satisfying the torque command at all times, based on the condition of internal and external variables to the vehicle.

Torque Distribution Control Design in this study

In order to establish torque distribution, rule based fuzzy control is designed based on the modes of operation of a vehicle, and energy flow in each mode.

Vehicle Operating Modes and Torque Relation

| Start-up | | $\left|T_l\right| = 0, \ T_{DC} > 0$ |

| Acceleration | | $\left|T_l\right| > 0, \ T_{DC} > 0$ |

| Cruise | | $\left|T_l\right| > 0, \ T_{DC} = 0$ |

| Deceleration | | $\left|T_l\right| > 0, \ T_{DC} < 0$ |

| Stationary | | $\left|T_l\right| = 0, \ T_{DC} = 0$ |
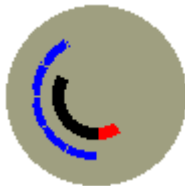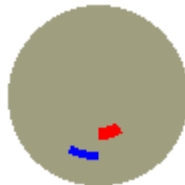
Tc

Tl

T_{DC}
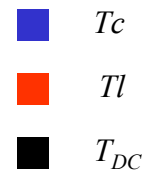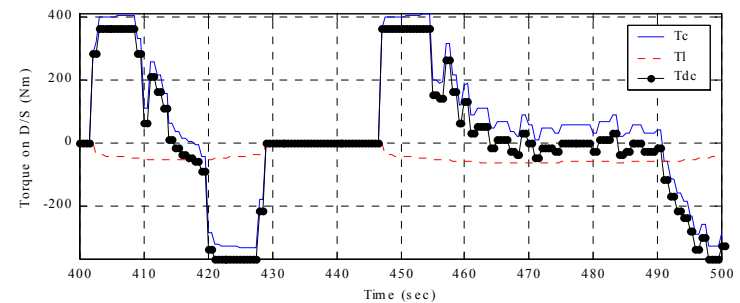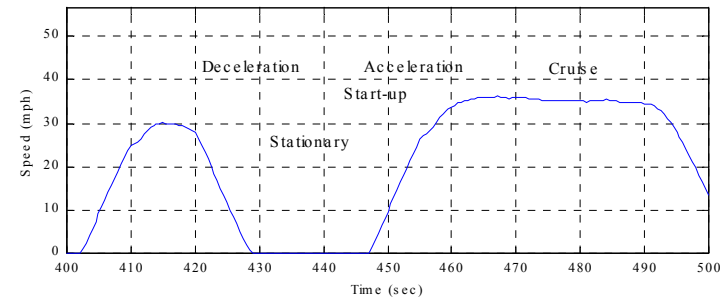
Energy Flow in Modes of Operation of a vehicle
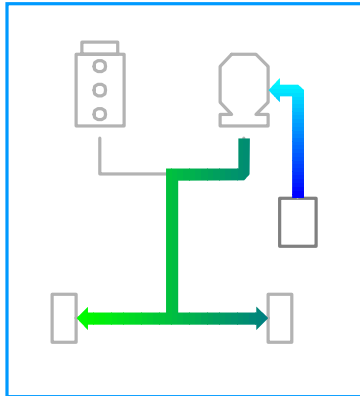
1. Start-up mode

The instant start is accomplished by using the electric motor with the energy coming from the battery.
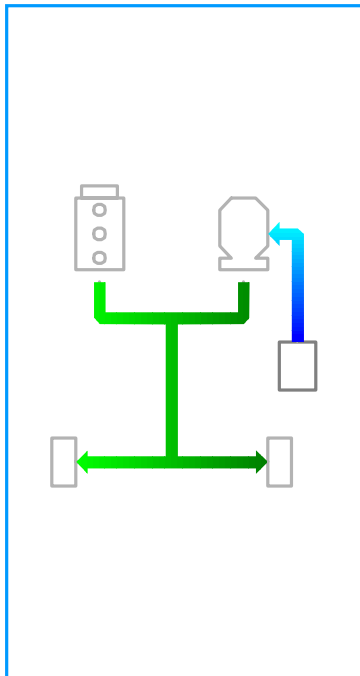
2. Acceleration mode

• During acceleration and other high load conditions such as climbing a steep slope, current from the battery is supplied to the motor.
• The output of the motor is used together with the gasoline engine's output so that power available for acceleration is maximized.
• The amount of the motor assist can be determined by the state of charge (SOC) of a battery and other states of a vehicle.

The following strategy is a basis for establishing a fuzzy rule base in the acceleration mode.

Case 1: SOC is HIGH
　　　　　Under Mild (light) acceleration: Motor partial assist
　　　　　Under Abrupt (heavy) acceleration: Motor full assist
Case 2: SOC is LOW
　　　　　When the engine is operating under WOT, Motor partial assist

Energy Flow in Modes of Operation of a vehicle
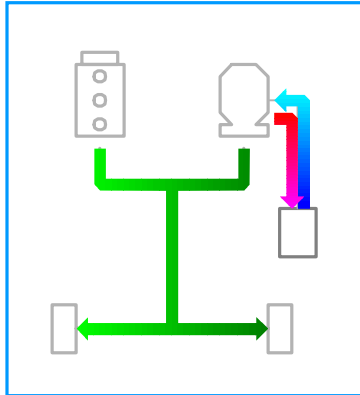
3. Cruise mode

- When a vehicle is cruising at constant speed,
  a small amount of torque is needed to maintain its speed.
- The function of the electric motor can be changed to those of the generator.
- Some engine output is used by the motor(/generator) being operated
  in *generation mode* to charge the battery.
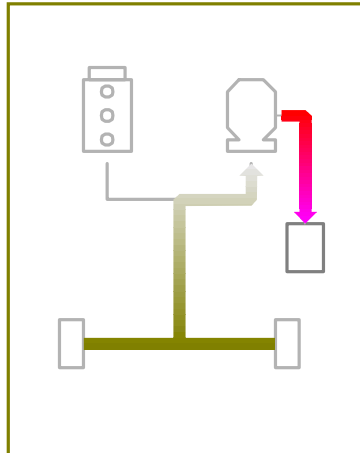
4. Deceleration / Regenerative braking mode

There are two deceleration modes:
(1) Acceleration pedal release mode (not on brake pedal)
  - A vehicle slows down gradually.
  - Partial charge can be acquired.
(2) Brake pedal push mode
  - A vehicle slows down rapidly.
  - A higher amount of regeneration will be allowed.
  - During light pedal application, motor/generator slows down the vehicle.
  - Under heavy pedal application, mechanical brake also comes into play.
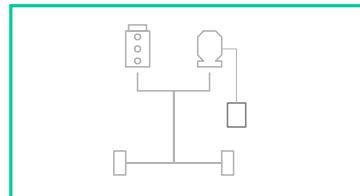
5. Stationary mode

When a vehicle is stationary, such as when sitting at a stop light, the gasoline
engine is typically turned off. As such there is no energy flow in the powertrain.

Variables used in Fuzzy Torque Distribution Control

Input variables to FTDC are chosen to represent a vehicle's operating modes and states of a vehicle.

Output variable of FTDC is a torque increment for the engine.

Torque required for acceleration or deceleration
T_{DC}

Engine speed
N_E

State of Charge of a Battery
SOC

FTDC

Torque increment for the engine
ΔT_{ec}
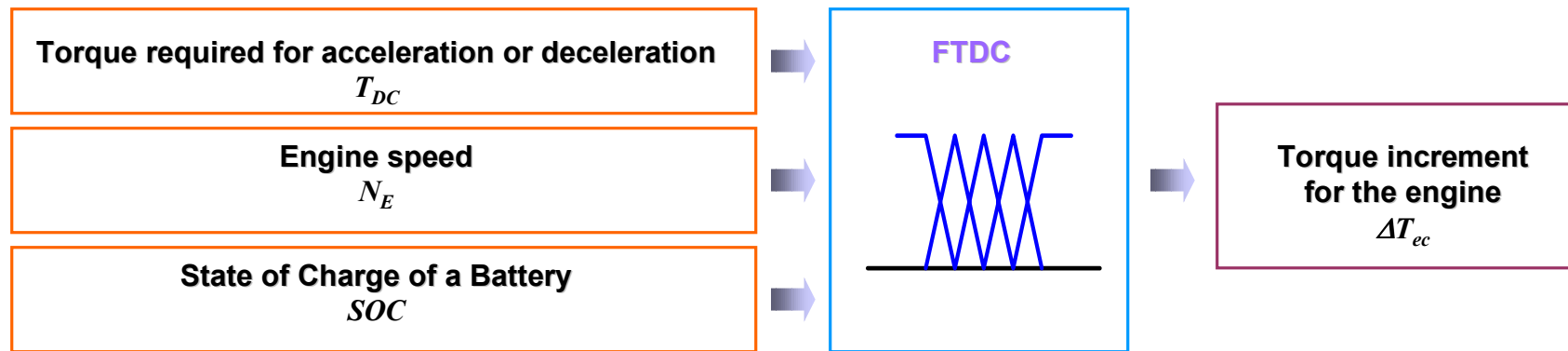
- T_{DC} is an external variable and represents the driver's intention (or driving condition).
- N_E and SOC are internal variables and represent the states of a vehicle. Especially, the engine speed is used for representing the road load torque.

$$T_l = f_1(\alpha, \omega) = f_2(\alpha, N_E) = f(N_E)$$

Mechanical Connection between wheel and engine

Flat road grade $\alpha = 0$

- This should be added to the current engine torque to make engine torque command (T_{ec}).

Membership Functions in FTDC

| Torque required for acceleration T_{DC} |
| Engine speed N_E |
| State of charge SOC |
| Torque increment for the engine ΔT_{ec} |
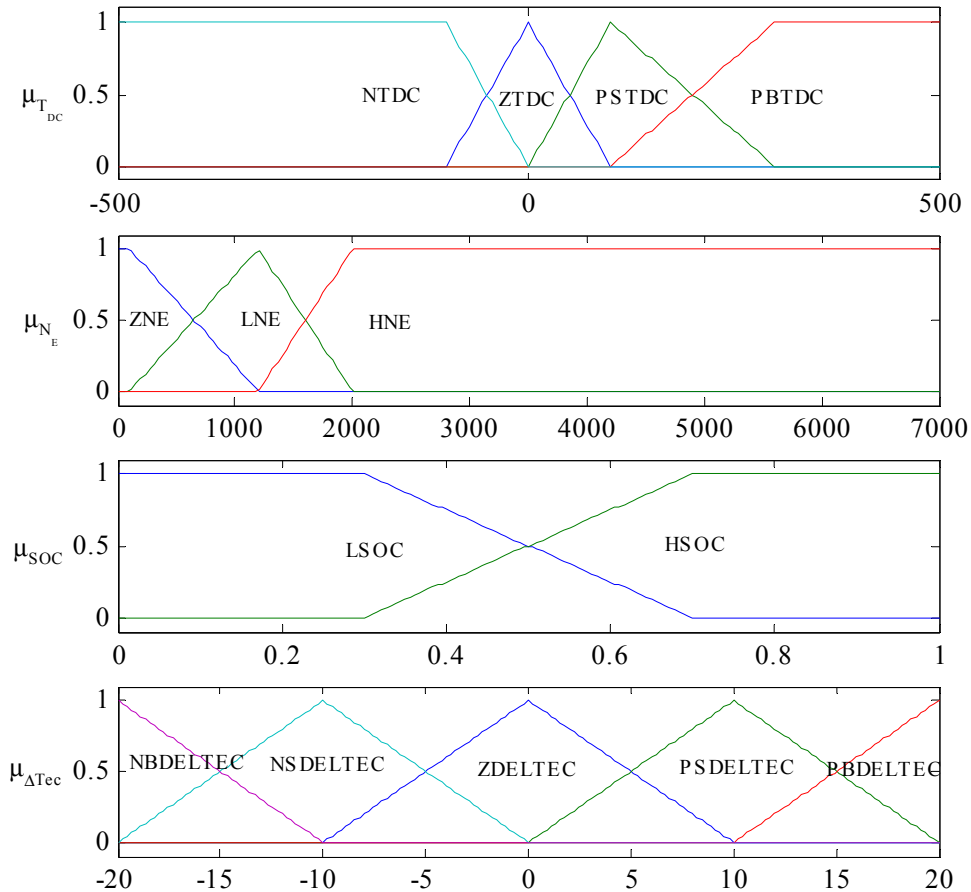
Simulation

Three types of Energy Management Strategy for the Torque Distribution Control

Electrically Peaking strategy	Motor Assist strategy	ICE Peaking strategy **(Internal Combustion Engine)**
Engine: primary source Motor: partial assist	Both Engine and Motor are used	Engine: assist Motor: primary source

Fuzzy Rule Base 1:

Electrically Peaking - Main: Engine, Assist: Motor

Rule Modes	Antecedent			Consequent
	T_{DC}	N_E	SOC	ΔT_{ec}
Start-up	PB	ZE		ZE
Acceleration	PS PB PS PB PS PB PS PB	L L H H L L H H	H H H H L L L L	PB PB PB PB PB PB PB PB
Cruise	ZE ZE ZE ZE	L H L H	H H L L	PS PS PB PB
Deceleration	N			NB
Stationary	ZE	ZE		ZE

⬆ FTDC is designed for the engine to provide the power, during the acceleration and cruise mode.

Simulation Result 1
Electrically Peaking - Main: Engine, Assist: Motor
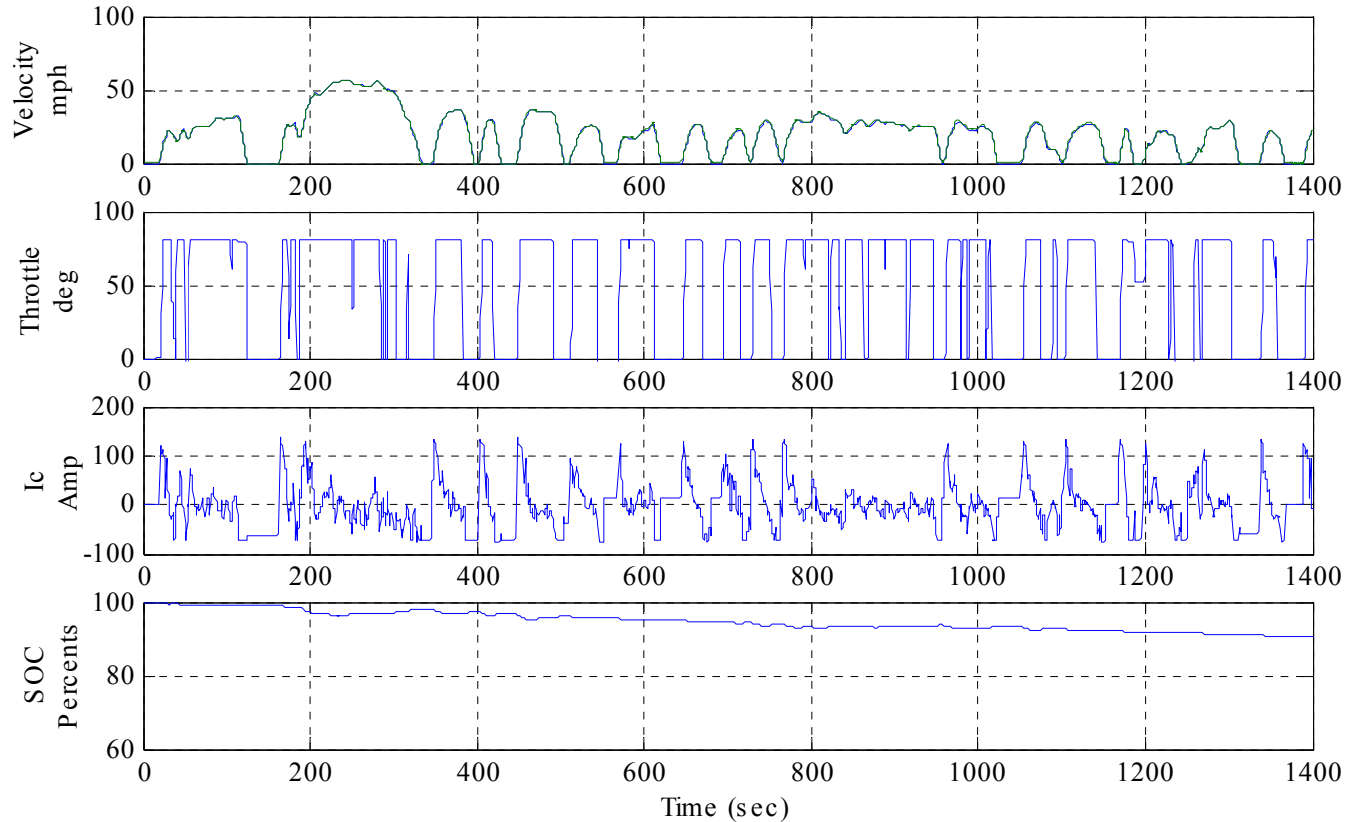
Average MPG = 62.47, DOD = 9.71 %, CO = 0.7278 g/mi, NOx = 0.4309 g/mi, HC = 0.0671 g/mi

As expected, during the acceleration and cruise mode,
FTDC force the engine to be operated at full throttle at all times.

Fuzzy Rule Base 2
(Partial Motor Assist)

Modes / Rule	Antecedent			Consequent
	T_{DC}	N_E	SOC	ΔT_{ec}
Start-up	PB	ZE		ZE
Acceleration	PS	L	H	ZE
	PB	L	H	PS
	PS	H	H	ZE
	PB	H	H	PS
	PS	L	L	PS
	PB	L	L	PS
	PS	H	L	PB
	PB	H	L	PB
Cruising	ZE	L	H	ZE
	ZE	H	H	ZE
	ZE	L	L	PS
	ZE	H	L	PS
Deceleration	N			NB
Stationary	ZE	ZE		ZE

⬆ **This rule is designed in consideration for the SOC.**
- Under high SOC, the engine is run when the driver's intention is relatively high.
- Under low SOC, the engine is run to charge the battery if surplus power is available.

Simulation Result 2
(Engine & Motor Assist)
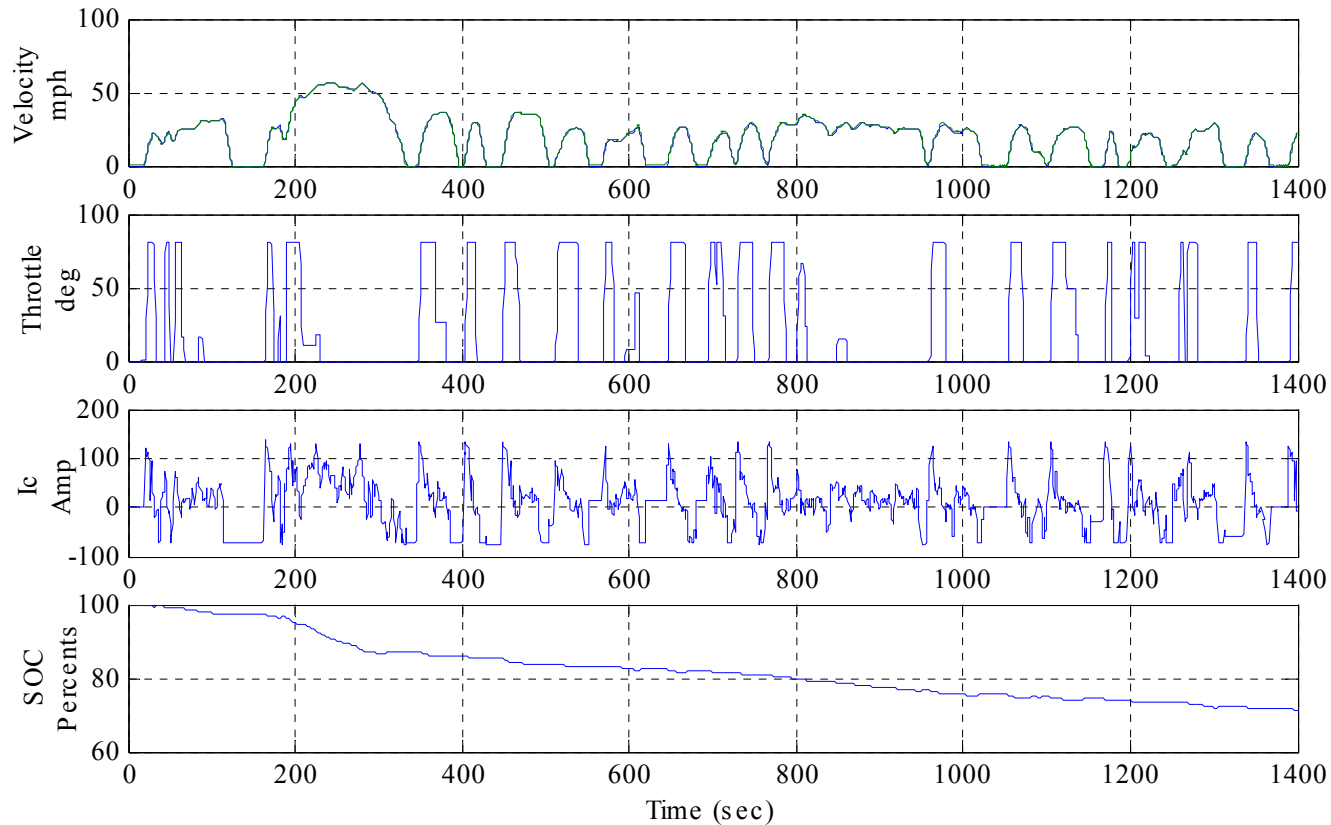
Average MPG = 172.67, DOD = 28.77 %, CO = 0.2651 g/mi, NOx = 0.1023 g/mi, HC = 0.0393 g/mi

During the acceleration mode, the engine is used to provide the power.
  But in the cruise mode (or low load condition), No engine power is used.

Fuzzy Rule Base 3
ICE Peaking (Engine Assist) - Main: Motor, Assist: Engine

Rule Modes	Antecedent			Consequent
	T_{DC}	N_E	SOC	ΔT_{ec}
Start-up	PB	ZE		ZE
Acceleration	PS PB PS PB PS PB PS PB	L L H H L L H H	H H H H L L L L	NS NB NS NB ZE ZE ZE ZE
Cruising	ZE ZE ZE ZE	L H L H	H H L L	NS NB ZE ZE
Deceleration	N			NB
Stationary	ZE	ZE		ZE

⬆ FTDC is designed for the motor to provide power for all operating mode (except start-up and stationary mode) if SOC is high.

Simulation Result 3

ICE Peaking (Engine Assist) - Main: Motor, Assist: Engine
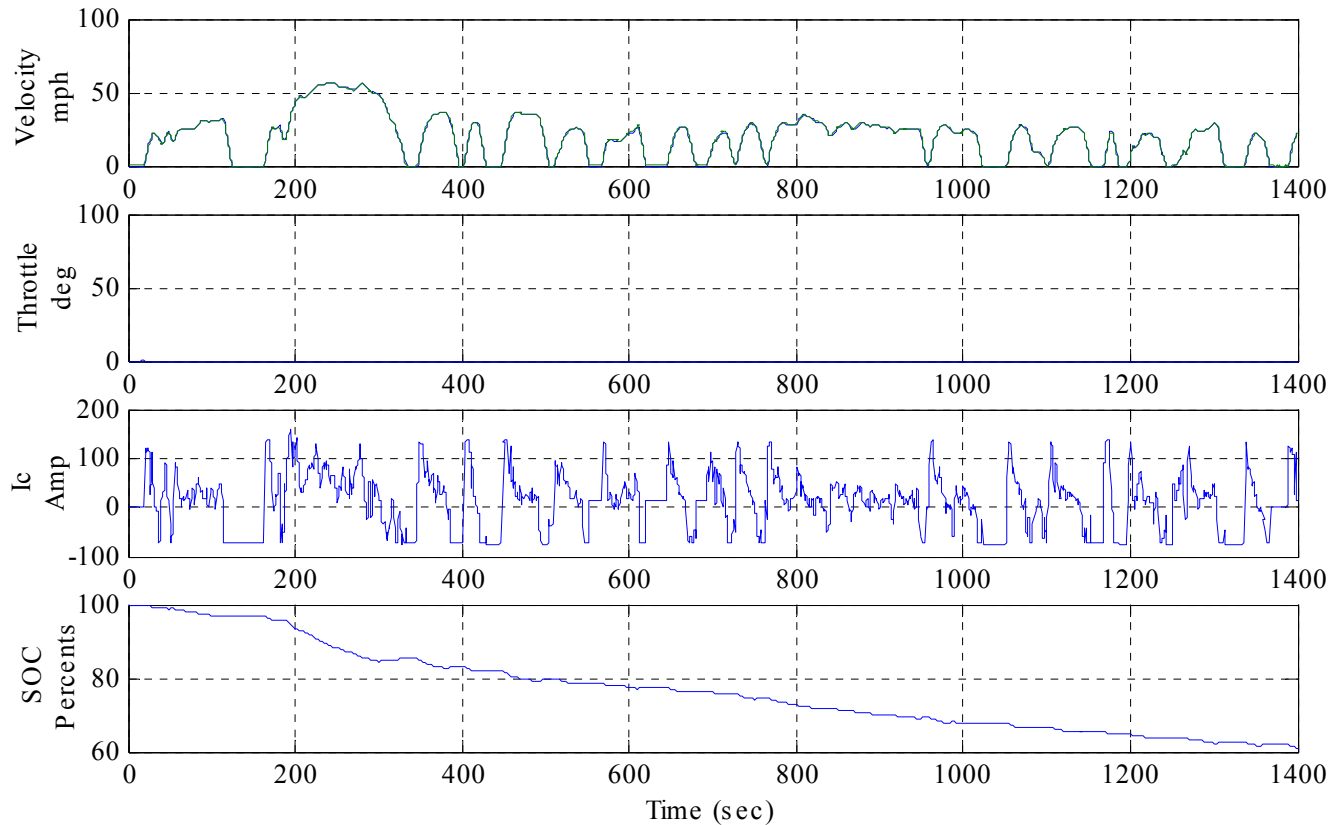
Average MPG = inf, DOD = 38.88 %, CO = 0 g/mi, NOx = 0 g/mi, HC = 0 g/mi

No engine is used for all times.
Depth of Discharge of a battery is larger than those of in Electrically Peaking.

Fuzzy Torque Distribution Control Performance Results (FTP75 Urban Cycle)

Rule Modes	Antecedent			Consequent, ΔT_{ec}		
	T_{DC}	N_E	SOC	Electrically Peaking Main: Engine	Partial Motor Assist	ICE Peaking Main: Motor
Start-up	PB	ZE		ZE	ZE	ZE
Acceleration	PS	L	H	PB	ZE	NS
	PB	L	H	PB	PS	NB
	PS	H	H	PB	ZE	NS
	PB	H	H	PB	PS	NB
	PS	L	L	PB	PS	ZE
	PB	L	L	PB	PS	ZE
	PS	H	L	PB	PB	ZE
	PB	H	L	PB	PB	ZE
Cruising	ZE	L	H	PS	ZE	NS
	ZE	H	H	PS	ZE	NB
	ZE	L	L	PB	PS	ZE
	ZE	H	L	PB	PS	ZE
Deceleration	N			NB	NB	NB
Stationary	ZE	ZE		ZE	ZE	ZE

		Electrically Peaking	Partial Motor Assist	ICE Peaking
Fuel Economy (Avg. MPG)		62.47	127.67	inf
Depth of Discharge (%)		9.71	28.77	38.88
Emission (g/mi)	CO	0.7278	0.2651	0
	NOx	0.4309	0.1023	0
	HC	0.0671	0.0393	0

CO: Carbon Oxide, NOx: Family of Nitrogen Oxide, HC: Hydro Carbon

Conclusions

♦ **Fuzzy Torque Distribution Control (FTDC)** is designed simply based on **the vehicle's operating modes** and **an empirical knowledge of energy flow** in each mode of operation.

♦ Simulation results show that

  - FTDC can manage energy flow in the parallel hybrid while meeting the driver demand.

  - FTDC allows the users to select the different energy management strategies for their preference.

♦ Future Study

  - Focus on the design of adaptive FTDC that can manage the energy flow more efficiently.

Multiobjective Optimal Torque Distribution for a Parallel Hybrid Electric Vehicle

Presentation

by

Reza Langari and Jong-Seob Won

Texas A&M University
Mechanical Engineering Department

August 28, 2001

Objective

Find an Optimal Torque Distribution Control

for a Parallel Hybrid Vehicle.

Hybrid vehicle Modeling

- Nonlinear State Equations for the vehicle model*

$$\dot{\omega} = f_1(\omega, P_m; I_c, T_{bc})$$

$$\dot{P}_m = f_2(\omega, P_m; \theta)$$

$$\dot{SOC} = f_3(\omega; I_c)$$

ω : Drive shaft speed

P_m : Manifold pressure

θ : throttle setting

I_c : motor current

T_{bc}: brake torque command

- Output Equations

$$\dot{M}_f = o_1(\omega, P_m; \theta)$$

$$\dot{DOD} = o_2(\omega; I_c)$$

$$\dot{CO}, \dot{NO}_x, \dot{HC} = e_i(\omega, P_m)$$

$$T_e = g_1(\omega, P_m)$$

$$T_m = g_2(\omega; I_c)$$

$\dot{M}_f$: Fuel flow rate,

$\dot{DOD}$: Depth of Discharge rate

$\dot{CO}, \dot{NO}_x, \dot{HC}$: Emission rates,

Te : Engine torque

Tm : Motor torque
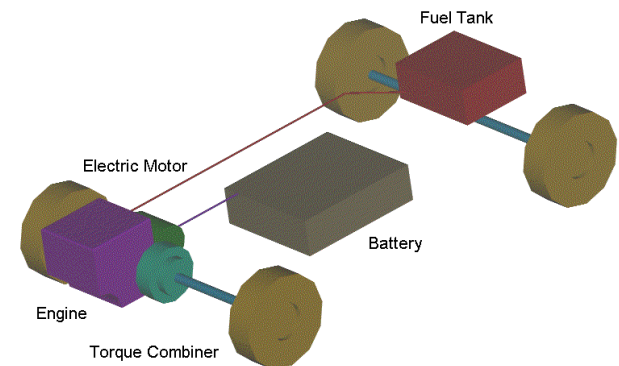
Typical parallel hybrid drivetrain

* Powertrain component models are taken from Buntin's thesis [1994].

Vehicle Modeling and Torque Relation
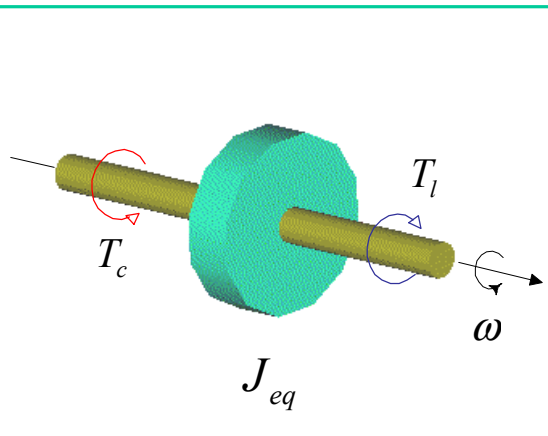
Drive Shaft Model equation:

$$T_c - T_l = J_{eq} \times \frac{d\omega}{dt}$$

J_{eq} : **Equivalent inertia of a vehicle**

where T_c : **Torque command from the driver**

$$T_c = T_{ec} + T_{mc} - T_{bc}$$

T_{ec} : **Engine torque command on the drive shaft**

T_{mc} : **Motor torque command on the drive shaft**

T_{bc} : **Brake torque command on the drive shaft**

T_l : **Road load torque**

T_{DC} : **Torque required for acceleration or or deceleration**

$$T_{DC} = T_c - T_l$$

* Powertrain component models are taken from Buntin's thesis [1994].

Problem Statement

Driver's Intention to move a vehicle from ω_1 to ω_2

Driver's Accelerator or Brake pedal Application driver's torque command Tc

- The application of the accelerator or the brake pedal by the driver, which is directly converted into the driver's torque command, implies that the vehicle will be accelerated or decelerated to a desired speed while overcoming the road load.

Start Push

Keep Pushing

Tc

Torque Distribution

- **Engine** T_{ec}
- **Motor** T_{mc}
- **Brake** T_{bc}

- This driver torque command can be met from the torque generated by the engine, the motor, and the brake.

$$T_{ec} + T_{mc} - T_{bc} = T_c$$

- This relation imposes **the nonlinear constraint** on the torque distribution problem !!

- There are INFINITE sets of solution satisfying the above **torque balance constraint**.

Problem Statement (cont'd)

- One possible solution : $\{\theta_{ki}, I_{cki}\}$

Maximum torque in the EM

T_{mc}

Maximum torque in the ICE

T_c

θ_{WOT}

T_e T_{ec} θ_k

ω_k

drive shaft speed

Minimum torque in the EM

Driver Torque Demand
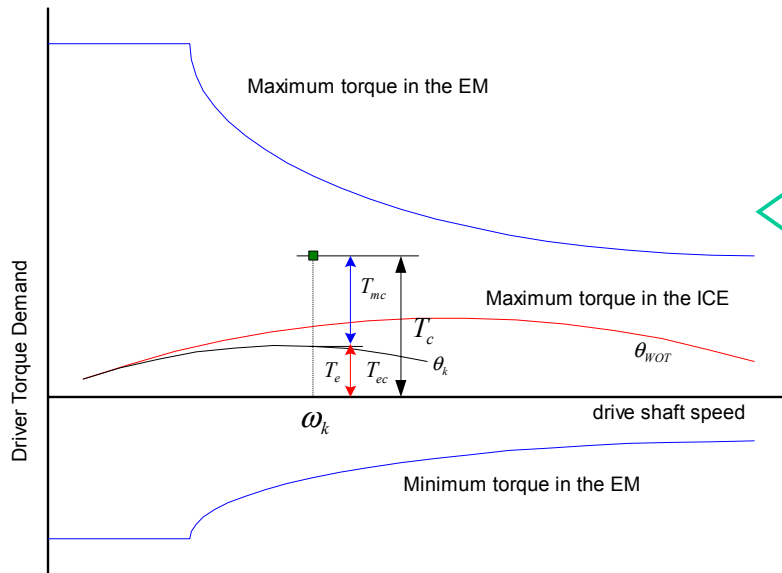
In the region where no mechanical brake is needed (T_{bc}=0), one FEASIBLE solution (*a set of decision variables - throttle setting (θ) and electric current (I_c)*) to the torque balance constraint is easily given in terms of the left side equation.

where

T_c is the driver's torque command that is given at the moment of the pedal application.

$T_e(\omega_k, P_{mk})$ is the engine torque that is *currently* being generated under the current throttle setting, θ_k.

$T_m(\omega_k, I_{cki})$ is the motor torque, which together with the engine torque is expected to meet the driver's torque demand.

Choose $\theta = \theta_k = \theta_{ki}$

$$\underbrace{T_e(\omega_k, P_{mk})}_{T_{ec}} + \underbrace{T_m(\omega_k, I_{cki})}_{T_{mc}} = T_c$$

$$I_c = I_{cki} = T_m^{-1}(T_c, T_e(\omega_k, P_{mk}))$$

One feasible solution can be chosen as

current throttle setting, θ_{ki}

electric current I_{cki} from the torque balance calculation

Problem Statement (cont'd)

- Another solution: $\{\theta_k, I_{ck}\}$
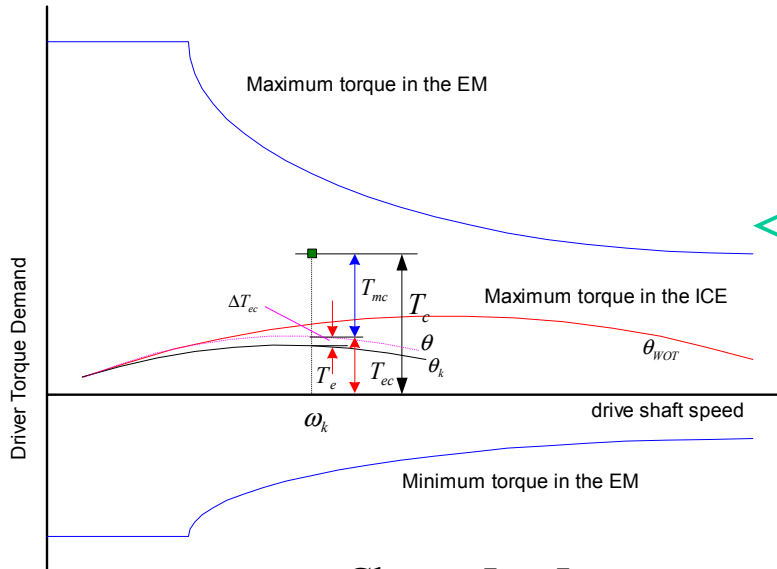
As one choose a specific motor current, I_{ck}, to meet the driver's torque command, the throttle setting should also be changed to generate the increment of the engine torque, $\mathbf{\Delta T_{ec}}$ which can be added to the current engine torque, $\mathbf{T_e(\omega_k, P_{mk})}$, to satisfy the overall driver's demand.

Choose $I_c = I_{ck}$

$$\underbrace{\mathbf{T_e(\omega_k, P_{mk}) + \Delta T_{ec}}}_{\mathbf{T_{ec}}} + \underbrace{\mathbf{T_m(\omega_k, I_{ck})}}_{\mathbf{T_{mc}}} = \mathbf{T_c}$$

$$\theta = \theta_k \leftarrow \theta_{ki} + \Delta\theta$$

Another feasible solution can be chosen as **throttle setting**, θ_k, and **electric current** I_{ck}

At this point, the problem to be solved is to find the proper throttle setting and motor current.

Problem Formulation

- Generally, the solution to the optimal torque distribution problem is ultimately dependent on the objective defined.

- For the hybrid vehicle using a gasoline engine and an electric motor for propulsion, the fuel and the battery are the primary energy sources.

With this in mind, the problem of optimal torque distribution for the parallel hybrid electric vehicle is formulated as a *multiobjective nonlinear optimization problem* with the objectives of minimization of fuel and battery usage.

Minimize Fuel flow rate

Minimize Depth of discharge rate

    Subject to

        Nonlinear constraints – torque balance,

        Lower and upper bounds for the decision variables, …

Our Approach

Summary of the proposed approach ….

Multiobjective Nonlinear Optimization Problem

Torque Balance Constraint Linearization

Objective Functions Linearization

Single objective Transformation via Fuzzy logic based approach

Single objective Transformation via Fuzzy logic based approach

Single Objective Linear Optimization Problem

Single Objective Linear Optimization Problem
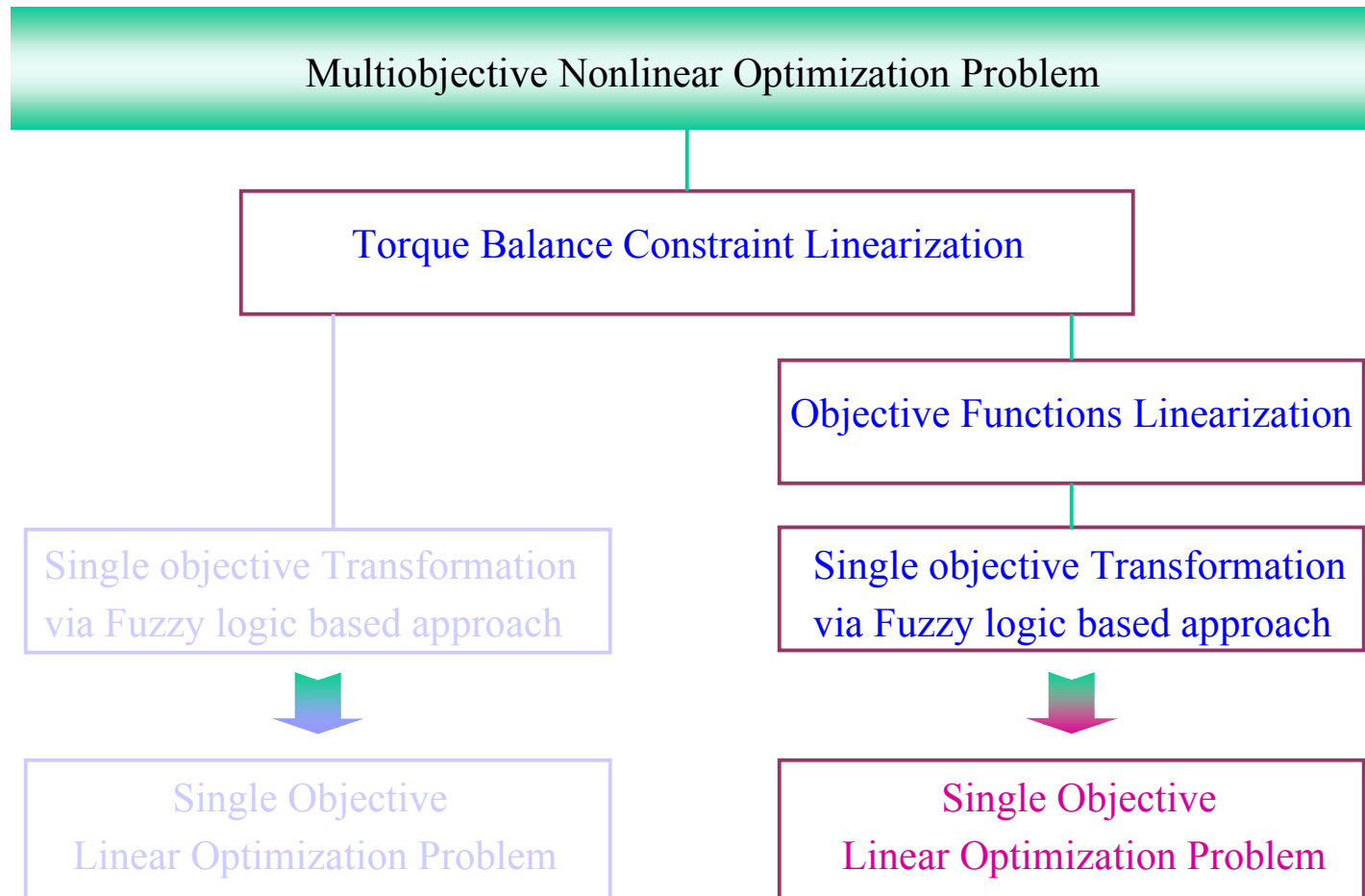
Flow chart for the proposed algorithm

Step 1: Find Initial feasible set of decision variables

- From the driver's torque command and current values of the states and variables, Calculate I_{cki} from the torque balance constraint

$$T_e(\omega_k, P_{mk}) + T_m(\omega_k, I_{cki}) = T_c$$

and set $\theta_k = \theta_{ki}$.

Step 2: Torque Balance Constraint Linearization

$$T_e(\omega_k, P_{mk}) + \Delta T_{ec} + T_m(\omega_k, I_{ck}) = T_c$$

$$\frac{T_{e\,max}(\omega_k)}{\theta_{WOT}} \times \theta_k + c(\omega_k) \times I_{ck} = T_c$$

Step 3: Objective Functions Linearization

Using the initial feasible set from step 1 as base points.
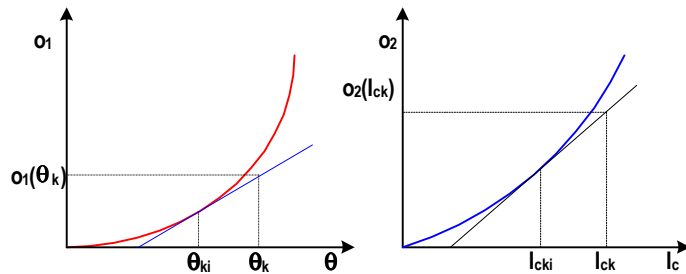
Step 4: Single Objective Transformation

By considering the worst case of energy consumption.
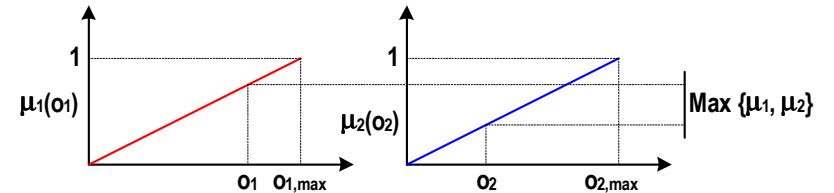
Step 5: Transformation of minimax problem into minimization problem

Linearization of Torque balance constraint

- Linearized Torque Balance Constraint is obtained by considering the extreme cases of the engine operation.

- If the engine is operated at Wide-Open-Throttle (WOT),

  then the engine torque command (T_{ec}) is equal to the maximum engine torque ($T_{e\,max}$).

- If only electric motor is to provide the torque needed to meet the driver's demand,

  then the throttle setting should be adjusted to make the current engine torque null.
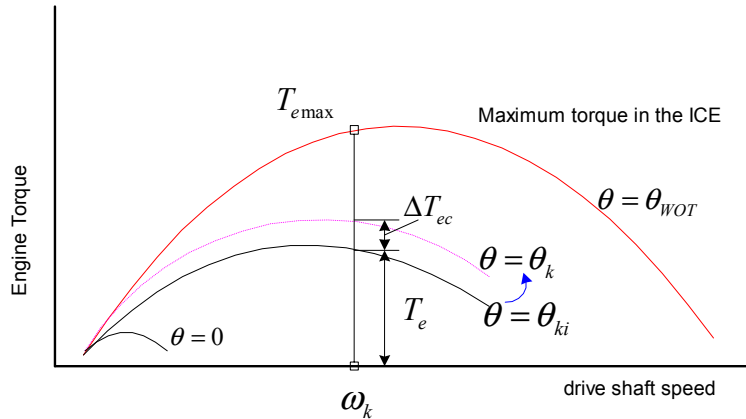
$$\underbrace{T_e(\omega_k, P_{mk}) + \Delta T_{ec}}_{T_{ec}} + \underbrace{T_m(\omega_k, I_{ck})}_{T_{mc}} = T_c$$

$$\frac{T_{e\,max}(\omega_k)}{\theta_{WOT}} \times \theta_k + c(\omega_k) \times I_{ck} = T_c$$

Linearization of Objective functions

- Linearization of objective functions is accomplished by using the initial feasible points $\{\theta_{ki}, I_{cki}\}$ as base points.

$$\dot{M}_f = \begin{cases} .00032940450025\theta^2 - .008235112561 & \text{if } P_m \leq \tfrac{1}{2}P_a \\ .0006588090053(\theta^2 - 25)\sqrt{.06802721088P_m - .004627701412P_m^2} & \text{if } P_m > \tfrac{1}{2}P \end{cases}$$

$$\dot{DOD} = \begin{cases} .2631578948I_c^2 + 3.881578948I_c\omega & \text{if } \omega \leq 80 \\ .2631578948I_c^2 + 310.5263159I_c & \text{if } \omega > 80 \end{cases}$$
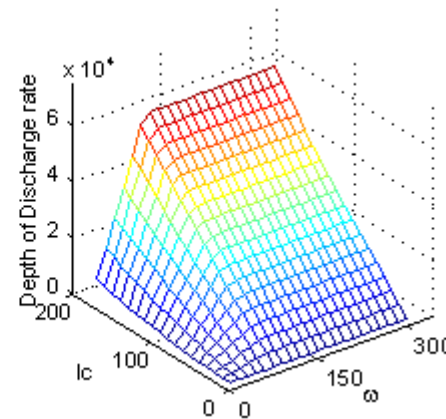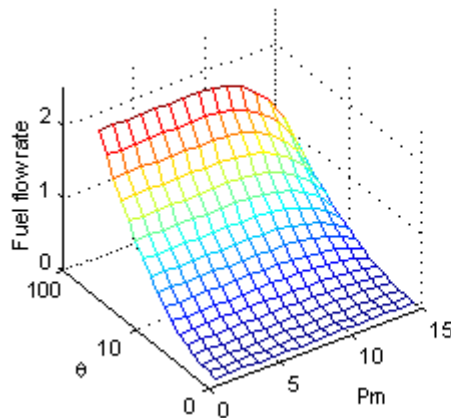
Single Objective Transformation

- In this study, a fuzzy logic based approach is used to transform the given multiobjective problem into a single objective problem.

- Since the objectives defined here are minimization of fuel and battery energy consumption, it is reasonable to consider **the worst case of the energy consumption** from either source as the objective.

Matching degree of fuel consumption	Matching degree of battery energy consumption	Worst case of energy consumption
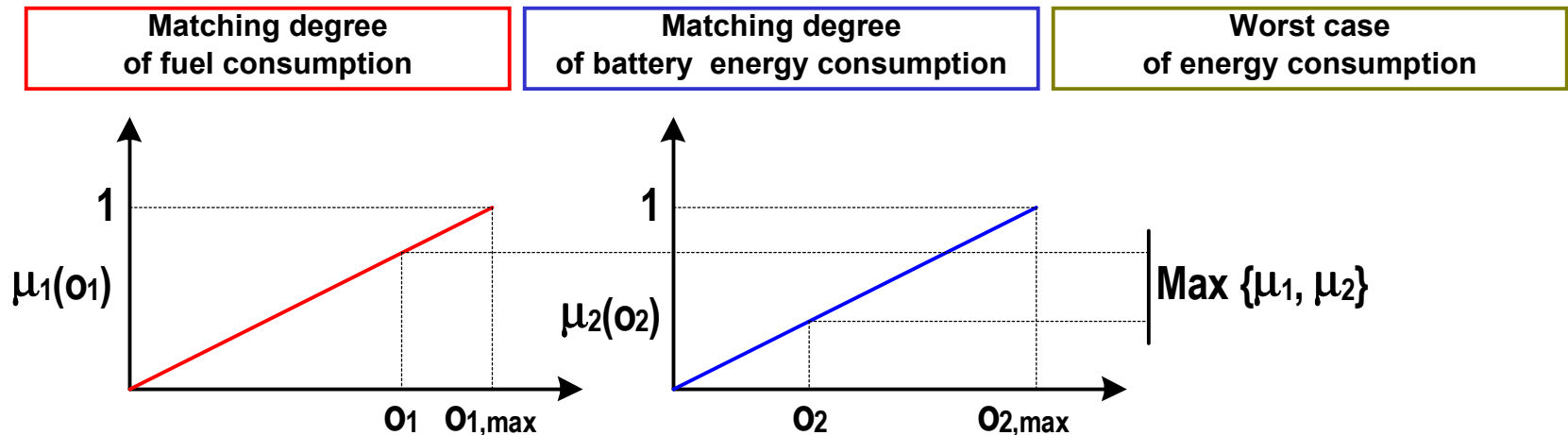
Min/Max into Minimization

- By considering the above steps, and transforming *minimax* problem into *min* problem, a multiobjective nonlinear optimization problem is recast as a single objective linear optimization problem as follows:

Min { max[$\mu_1(o_1)$, $\mu_2(o_2)$] }
Subject to
$\quad\quad \alpha \times \theta_k + \beta \times I_{ck} = T_c$
$\quad\quad lb \leq \theta_k, I_{ck} \leq ub$
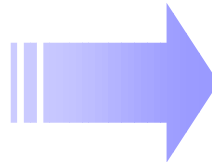
Min z
$\quad$**Subject to**
$\quad\quad\quad \mu_1(o_1) \leq z$
$\quad\quad\quad \mu_2(o_2) \leq z$
$\quad\quad\quad \alpha \times \theta_k + \beta \times I_{ck} = T_c$
$\quad\quad\quad lb \leq \theta_k, I_{ck} \leq ub$
$\quad\quad\quad 0 \leq z \leq 1$

Simulation

In order to evaluate the proposed method for optimal torque distribution,

two short driving courses from the FTP75 driving cycle are selected and tested.

Simulation Results – driving course I

Linear Optimization	Nonlinear Optimization	Performance Results
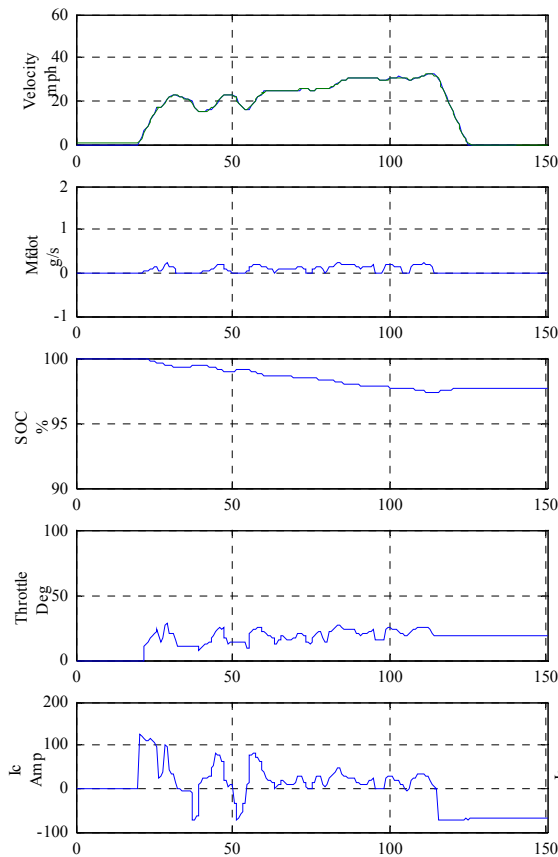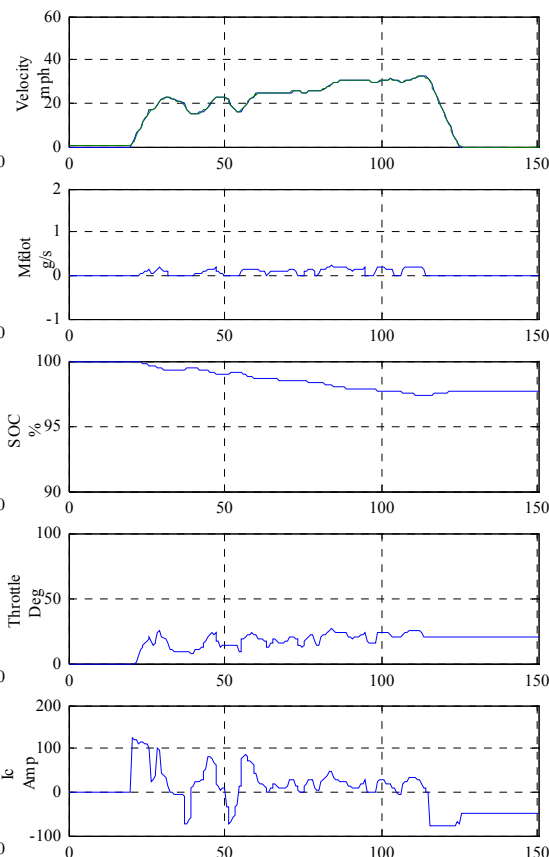
	Linear Optiml-zation	Nonlinear Optimization			
		[0,0]	EP	MA	IP
Average MPG	209.67	223.36			
DOD (%)	2.35	2.39			
CO (g/mi)	0.1980	0.1851			
Nox (g/mi)	0.0719	0.0689			
HC (g/mi)	0.0282	0.0268			
Computation Time (sec)	574.76	881.10	875.01	877.11	873.92

*Initial estimates for the nonlinear optimization solver are taken from the results of Fuzzy Torque Distribution Control Study.
Here initial estimate = {throttle setting, electric current}. EP=Electrically Peaking, MA=Motor Assist, IP=Internal Combustion Engine

Simulation Results – driving course II

Linear Optimization
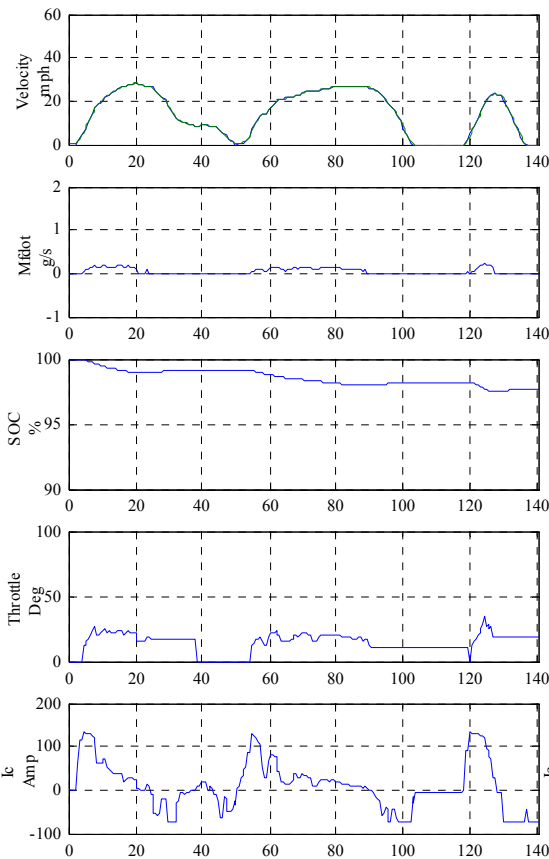
Nonlinear Optimization
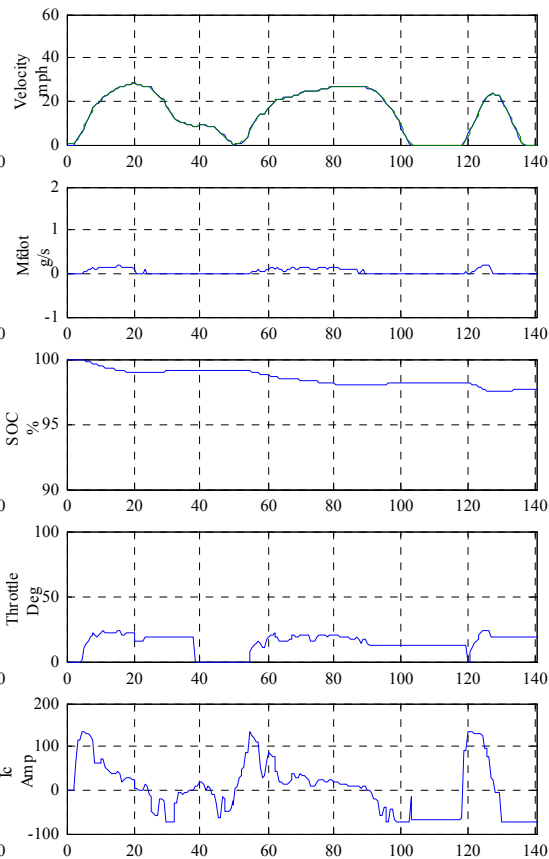
Performance Results

	Linear Optimi-zation	Nonlinear Optimization			
		[0,0]	EP	MA	IP
Average MPG	232.97	266.19			
DOD (%)	2.35	2.40			
CO (g/mi)	0.1745	0.1507			
Nox (g/mi)	0.0538	0.0492			
HC (g/mi)	0.0249	0.0222			
Computation Time (sec)	490.48	699.88	702.50	704.01	702.77

*Initial estimates for the nonlinear optimization solver are taken from the results of Fuzzy Torque Distribution Control Study.

Here initial estimate = {throttle setting, electric current}. EP=Electrically Peaking, MA=Motor Assist, IP=Internal Combustion Engine

Conclusion

- The problem of optimal torque distribution control for a parallel hybrid vehicle is formulated as a multiobjective nonlinear optimization problem.

- The multiobjective nonlinear optimization problem is recast as single objective linear optimization problem via the proposed method.

- Simulation results reveal that the proposed approach in this study offers significant computational advantage without impacting the optimization results.

FUZZY TORQUE DISTRIBUTION CONTROL FOR A PARALLEL-HYBRID VEHICLE

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ABSTRACT

A fuzzy torque distribution controller for energy management (and emission control) of a parallel-hybrid electric vehicle is proposed. The proposed controller is implemented in terms of a hierarchical architecture which incorporates the *mode of operation* of the vehicle as well as empirical knowledge of energy flow in each mode. Moreover, the rule set for each mode of operation of the vehicle is designed in view of an overall energy management strategy that ranges from maximal emphasis on battery charge sustenance to complete reliance on the electrical power source. The proposed control system is evaluated via computational simulations under the FTP75 urban drive cycle. Simulation results reveal that the proposed fuzzy torque distribution strategy is effective over the entire operating range of the vehicle in terms of performance, fuel economy as well as emissions.

1. INTRODUCTION

Hybrid electric vehicles have great potential as new alternative means of transportation. One of the main issues in the design of these vehicles is energy management for fuel economy and emission control. For the parallel type hybrid electric vehicle, the energy management strategy plays a crucial role in the performance of the vehicle as well as in its fuel economy and emission control. In a hybrid vehicle two main power sources – an internal combustion engine and an electric motor – are utilized. Under the driver's demand, the engine, the motor or both power sources can be operated to power the vehicle. One problem at this point is how to distribute the driver's demand into each power source while achieving satisfactory fuel consumption and low emissions. A number of control strategies intended to cope with this problem have been presented in the literature [1-5]. In particular, at least two *logic based* energy management strategies for hybrid vehicle have been suggested in [1,2]. The approach proposed in [1] is implemented in terms of a control scheme designed to maximize the SOC (State of Charge of the battery) while meeting the driver's torque demand. Similarly in [2], a power split strategy is established via a rule-based control scheme whose main function is to assign the required power to the engine, to the battery or to both based on the SOC, the power demand, and the acceleration command.

Energy management strategies for hybrid vehicle using *fuzzy logic* are proposed in [3-5]. In particular, a fuzzy control strategy to maximize the fuel efficiency for a hybrid SUV is described in [3] wherein a fuzzy rule base is used to optimize the energy usage. Likewise, in [4] a torque control strategy for a parallel hybrid is presented based on a fuzzy rule-based strategy whereby the (diesel) engine is controlled to propel the vehicle or to be used for the battery charging while satisfying the requirements on NO_x emissions. Finally, fuzzy decision making is used in [5] in which the throttle and the armature current demands are decided by a fuzzy decision maker with the pedal stroke as the input.

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In the studies described above, which are representative of a more extensive set of references on energy management and emission control for hybrid vehicles, the control strategies used are generally single layered; i.e. the controller implements a single set of rules that is assumed to be adequate for the entire range of operation of the vehicle. In our view this approach does not adequately reflect the reality of operation of hybrid vehicles, which must perform well across a spectrum of operating regimes, i.e., acceleration, cruise, high speed cruise, deceleration and so on. Accordingly, in this study a two layer *hierarchical* fuzzy logic based torque distribution control strategy is proposed that is meant to overcome the shortcoming of the aforementioned approaches.

The proposed approach, hereafter referred to as Fuzzy torque distribution control (FTDC), makes use of the notion of *mode of operation* of the vehicle and further incorporates empirical knowledge of operation of the vehicle as follows:

(1) Each mode of operation, i.e. acceleration, deceleration, cruise and so on, is associated with a specific set of rules that are activated when the vehicle is in the given mode.

(2) The resulting torque distribution strategy is shown to provide a more effective means of operating a parallel hybrid than single layer classical or fuzzy logic based torque distribution strategies [1-5].

This paper is organized as follows. The hybrid vehicle configuration considered in this study is briefly described in Section 2. Torque distribution control strategy for a parallel hybrid electric vehicle using fuzzy logic is discussed in Section 3. Section 4 gives the explanation of the control algorithm, the vehicle's mode of operation, and energy flow in each mode. Section 5 discusses the fuzzy rule set for operation of the vehicle. The simulation results are discussed in Section 6. Finally, the conclusions are presented in Section 7.

2. HYBRID VEHICLE CONFIGURATION

The vehicle model in this study is a parallel-type hybrid electric vehicle. The powertrain component models are taken from [1]. The vehicle has a total mass of 1655 kg that is the sum of the curb weight of 1467 kg and the battery weight. The engine with a displacement of 0.77L and peak power of 25 kW is chosen. The electric motor is chosen to meet the acceleration performance (a zero to 60 mph in less than 15 seconds). In order to satisfy the requirement for acceleration, the motor with the power of 35 kW is selected. The battery capacity is 6 kW-h or 21.6 MJ with a weight of 188 kg and is chosen based on the estimated values of lead acid type battery used in a conventional car. The vehicle is simply modeled in terms of a drive-shaft oriented approach as shown in Fig. 1.

In connection with the figure, the dynamic model of the system is given by

$$T_c - T_l = J_{eq} \times \frac{d\omega}{dt}$$

where T_c is the driver torque command generated via the accelerator or the brake pedal, T_l is the road load torque due to the rolling resistance, wind drag, and road grade, and J_{eq} is the equivalent inertia of the vehicle. The right side of the above equation is equal to the torque needed for acceleration or deceleration of the vehicle. This value represents the driver's *intention,* based on the driving environment, and is called T_{DC}.
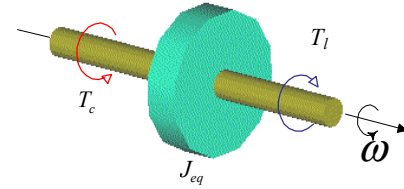
Figure 1. Drive shaft model

In order to accelerate (or decelerate) the vehicle while overcoming the road load, the driver torque command T_c should be applied to the drive shaft. This driver torque command is generated by the engine, the electric motor and the brake.

$$T_c = T_e + T_m - T_b$$

The above equation represents the primary constraint on the operation of the hybrid vehicle; i.e. this constraint must hold at each instant of time.

3. FUZZY TORQUE DISTRIBUTION DESIGN CONCEPT

In parallel-hybrid electric vehicles, the main control objective is to determine what portion of power from each source can be properly utilized to drive the vehicle while satisfying the driver torque demand. FTDC covers all of the vehicle's major operating modes including start-up, acceleration, cruise, light (mild) deceleration, and stationary modes. The driver torque command can be positive or negative depending on the operating mode of the vehicle. For the torque command above the minimum torque capability of the electric motor FTDC plays an important role, distributing the power demand to each power source while meeting the total driver's command. Under heavy deceleration, the torque command is below the minimum torque capability of the electric motor. In this mode, additional mechanical, as well as regenerative, braking is applied to meet the driver demand.

Regardless of the operating mode of the vehicle, the energy management strategy must consider the state of charge of the battery. This is particularly relevant during deceleration where the regeneration of electrical energy that would otherwise be wasted is accomplished. Specifically, the torque distribution

strategy in regenerative braking is simply to use the motor as the generator to slow the vehicle down and to return the kinetic energy of the vehicle to the battery in the form of electrical energy. The logic involved here is to switch the electric motor to a generator and to apply the mechanical brake only when the torque demand is beyond the minimum torque capability of the electric motor.

4. FUZZY TORQUE DISTRIBUTION CONTROL (FTDC)

The control algorithm used in this study is described as follows:

$$\text{If } T_c > T_{m\min}, \begin{cases} T_{ec} = T_e + \Delta T_{ec} \\ T_{mc} = T_c - T_e \\ T_{bc} = 0 \\ f_c = on \end{cases} \text{ else, } \begin{cases} T_{ec} = 0 \\ T_{mc} = T_{m\min} \\ T_{bc} = T_c - T_m \\ f_c = off \end{cases}$$

where $T_{m\min}$ is the minimum toque of the electric motor, f_c is the fuel command for the engine operation, and ΔT_{ec} is the output of the FTDC, which is heavily dependent on the selection of the fuzzy rule base representing the energy management strategy.

The vehicle operating modes are briefly represented as *start-up*, *acceleration*, *cruise*, *deceleration*, and *stationary mode*. In each mode, a different torque control strategy is required to control the flow of energy [6] and to maintain adequate reserves of energy in the storage devices. In order to illustrate the modes of operation of the vehicle, torque relation on the drive shaft in each mode is given as follows:

$$\text{Start-up: } |T_l| = 0, \ T_{DC} > 0$$
$$\text{Acceleration: } |T_l| > 0, \ T_{DC} > 0$$
$$\text{Cruise: } |T_l| > 0, \ T_{DC} = 0$$
$$\text{Deceleration: } |T_l| > 0, \ T_{DC} < 0$$
$$\text{Stationary: } |T_l| = 0, \ T_{DC} = 0$$

where $|T_l|$ is the torque required for maintaining the vehicle speed constant while overcoming the road load (rolling resistance, wind drag, and road grade). T_{DC} is the torque required for acceleration or deceleration of the vehicle. The summation of the two required torques is the total driver's torque command T_c that is generated by pushing the accelerator or the brake pedal.

The magnitude and sign of the required torque in each mode dictates the rule set used in that mode. In the start-up mode, instant start is accomplished by the electric motor alone, which has high torque capability at low speeds. When the vehicle is accelerated or driven on a non-level road, both sources of energy are used to meet the high load torque demand; the torque from the electric motor is used together with the torque from the engine so that power available for

acceleration is achieved. The amount of the motor assist is dependent on the torque required as well as the state of the vehicle. In particular, the state of charge (SOC) of the battery has priority over other states of the vehicle during high load conditions. The following is a brief description of the strategy used to design the rule set for each mode.

Acceleration: The control strategy in the acceleration mode is based on the SOC, which is a measure of the state of electrical energy providing the additional propulsion power to the vehicle. In particular, we consider two cases as follows:

Case 1: SOC is High,
    Under mild acceleration: Motor provides partial assist
    Under abrupt acceleration: Motor provides full assist
Case 2: SOC is Low,
    Motor provides partial assist when the engine is operating at Wide-Open-Throttle.

Cruise: When the vehicle is driving at a constant speed, a small amount of torque is needed to maintain the vehicle speed and to overcome the road load. In most cases, the engine in a hybrid vehicle is sized such that it is capable of satisfying not the peak power but the average power requirement. Under the charge-sustaining concept, the function of the electric motor can be switched to that of the generator to charge the battery for the next use if surplus power from the engine is available.

Deceleration: The regeneration of electric energy is accomplished during the deceleration mode. There are two types of deceleration modes: (1) Acceleration pedal release mode and (2) Brake pedal push mode. In the acceleration pedal release mode, the motor slows the vehicle down gradually and partial charge can be acquired. During the brake pedal push mode, the vehicle slows down rapidly and a higher amount of regeneration will be allowed. Under the light pedal application, the electric motor (or generator) slows down the vehicle. Mechanical brake also plays an important part in the heavy pedal application.

Idle condition: In the stationary mode, there is no energy flow in the powertrain. The gasoline engine is typically turned off except when the battery's SOC is low, in which case the gasoline engine is operated to run a generator that provides power to charge the battery. In this study, this task cannot be performed because there is assumed to be no transmission and the engine and the wheels are mechanically directly connected.

5. IMPLEMENTATION OF FTDC

The linguistic variables in the fuzzy rule set are chosen to describe the vehicle's operating modes and the states of the vehicle. As an external variable that describes the driving environment or driver's behavior (intention), the torque demand for acceleration or deceleration (T_{DC}) is selected. This command can be directly converted from the acceleration or

brake pedal application. The engine speed (N_E) and the battery's SOC are selected as internal variables of the vehicle. Specifically, the engine speed is used to infer the road load (T_l). The road load is a function of the road grade and the speed of the vehicle. No transmission device is present in the parallel hybrid model. Mechanical connection between the engine and the wheels converts the input argument for the speed of the vehicle to the engine speed. On the additional assumption of driving on a level road, the road load is just a function of the engine speed.

The output of the FTDC is the torque increment for the engine, ΔT_{ec}. This value should be added to the current engine torque, T_{ec}, to produce the engine torque command. The membership functions used in FTDC are presented in Fig. 2. The partitions of the membership functions are made in consideration for the system's characteristics and the responses of the powertrain components. Yet, there remain possibilities for choosing different sets of membership functions.

L: Low, H: High, N: Negative
NB: Negative Big, NS: Negative Small, Z: Zero,
PS: Positive Small, PB: Positive Big
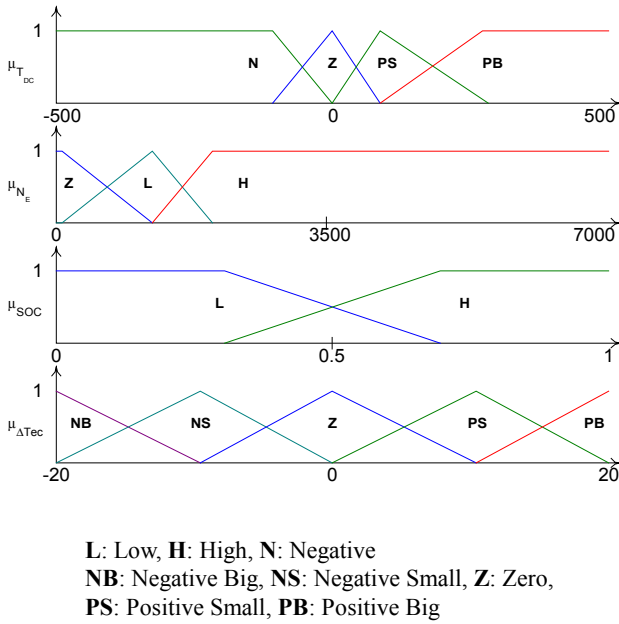
Figure 2. Membership functions of the Fuzzy Torque Distribution Control

Three different energy management strategies are considered for the torque distribution control of the parallel hybrid electric vehicle in this study: (1) Electrically peaking, (2) Internal Combustion Engine (ICE) peaking, and (3) an energy management strategy that lies halfway between (1) and (2). As mentioned, the mission of the FTDC is to assign the driver command to the engine and the motor while guaranteeing better fuel economy (and lower exhaust emissions) as well as better

battery SOC sustenance. Once the energy management strategy is chosen, the fuzzy rule sets for the modes of operation of the vehicle are determined. These rule sets are summarized in Table 1.

Table 1. Rule bases for the energy management strategies

	Antecedent			Consequent		
				Electrically Peaking	Motor Assist	ICE Peaking
	T_{DC}	N_E	SOC	ΔT_{ec}		
Start-up	PB	Z		Z	Z	Z
Acceleration	PS	L	H	PB	Z	NS
	PB	L	H	PB	PS	NB
	PS	H	H	PB	Z	NS
	PB	H	H	PB	PS	NB
	PS	L	L	PB	PS	Z
	PB	L	L	PB	PS	Z
	PS	H	L	PB	PB	Z
	PB	H	L	PB	PB	Z
Cruise	Z	L	H	PS	Z	NS
	Z	H	H	PS	Z	NB
	Z	L	L	PB	PS	Z
	Z	H	L	PB	PB	Z
Deceleration	N			NB	NB	NB
Stationary	Z	Z		Z	Z	Z

As shown in Table 1, the rule sets for different energy management strategies differ, reflecting the difference in the point of view implied by each strategy. For instance consider the rules for the acceleration mode where the electrically peaking strategy suggests a large (positive big or PB) change in the engine torque while the motor assist strategy suggests a milder action (zero, Z, positive small, PS, or positive big, PB) for the same set of conditions. Similarly during cruise, the electrically peaking strategy suggests a positive small (PS) or positive big (PB) engine torque increment while the motor assist strategy requires a milder action that varies from zero, Z, to positive big, PB, based on the current torque demand, engine speed and battery state of charge.

In general the different energy management strategies propose different actions for a given vehicle state resulting in different overall performance over the entire drive cycle. The next section discusses the results of the simulation studies that quantitatively establish this point.

6. SIMULATION RESULTS AND DISCUSSION

Computational simulations are performed to evaluate the proposed fuzzy torque distribution control system. Given the FTP75 Urban drive cycle, the three types of torque distribution control strategies mentioned above are tested.

In the *Electrically Peaking* energy management strategy, the prime source of energy is the engine. During most instances of acceleration and cruising modes, the propulsion for driving

comes from the engine power. The additional power comes from the motor and is used together with the engine power if the torque demand is greater than the torque provided from the engine. As shown in Fig. 3, the Electrically Peaking strategy keeps the engine throttle setting near the Wide-Open-Throttle (WOT) during most instances of acceleration while keeping the battery state of charge (SOC) at or above 90%. Table 2 shows the performance figures for this strategy where the depth of discharge at the end of the drive cycle is less than 10%.
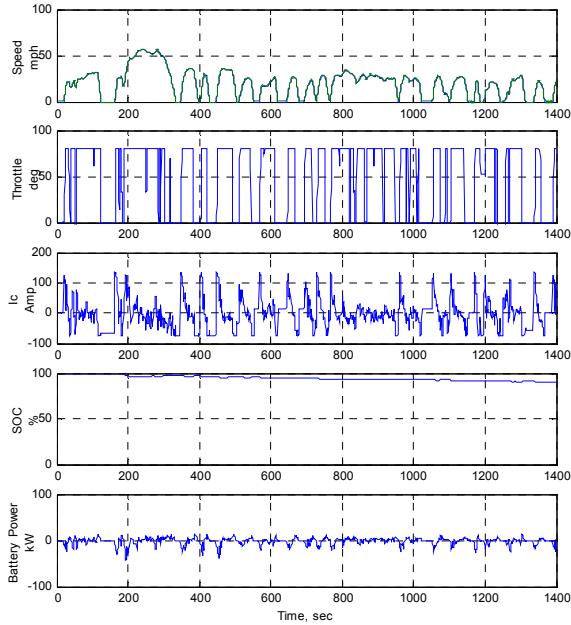
Figure 3. Performance results on the Electrically Peaking energy management strategy

The fuel economy of the electrically peaking strategy, however, is not as high as one might expect. This is in spite of the fact that the FTDC enables the engine to be operated at its high efficiency region from a thermodynamic standpoint, i.e. at Wide-Open-Throttle. The reason is that only a small portion of energy from the battery is actually used in this strategy. On the other hand, if one considers the overall cost of operating the vehicle and includes the cost/time associated with offline battery recharge, the electrically peaking strategy may not fare as poorly as it appears since the state of charge of the battery at the end of the drive cycle is high (90%+).

In the ICE Peaking energy management strategy, the main source of energy for driving is the electric motor. Fuzzy rule set is designed to provide the propulsion power from the motor when the battery's SOC is at a sufficient level (say at or above 50%.) It is observed from the simulation results that under the ICE Peaking strategy, no fuel is used; i.e. the engine remains

shut off during whole drive cycle (Figure 4). Table 2 shows the depth of discharge to be approximately 40% at the end of the drive cycle, reflecting considerable use of the battery during the operation of the vehicle. On the other hand, strictly from the standpoint of the engine, the fuel economy is at its ultimate best, i.e. infinite miles per gallon! It should be noted that, however, that this strategy is not particularly viable unless there is a strict requirement for zero emissions.
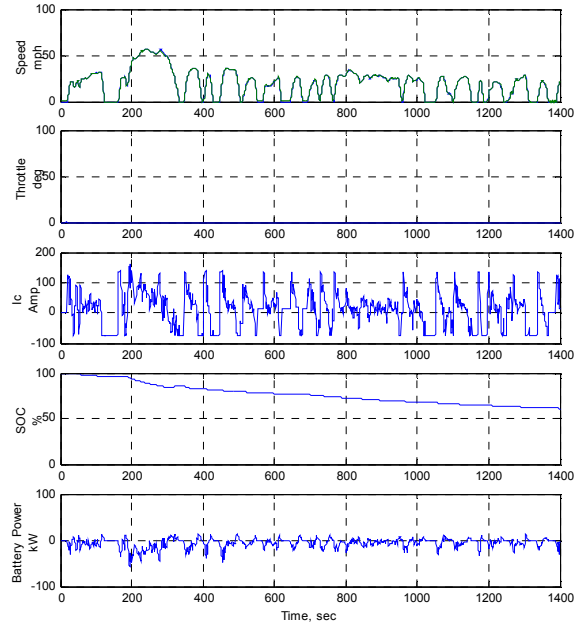
Figure 4. Performance results on the ICE Peaking energy management strategy

The realistic strategy to be considered in practice is that lying halfway between the Electrically Peaking and the ICE Peaking strategies, hereby referred to as the *charge-sustaining* strategy where the power from the engine and the motor can be used to drive the vehicle while meeting the driver torque command. As shown in the Fig. 5, the behavior of the engine and the motor reflect partial assist from the motor which is in turn reflected in only moderate loss of charge as noted in Table 2 (depth of discharge at 28.7% at the end of the drive cycle) in comparison with the ICE peaking strategy (with depth of discharge close to 40%). However, as stated earlier, the ICE peaking strategy is not viable in practice. Therefore, a more sensible comparison must be made with the electrically peaking strategy which results in only 10% depth of discharge. On the other hand, overall fuel economy, and emissions of the charge sustaining strategy is noticeably higher in comparison with the electrically peaking strategy, making it arguable the best of all three strategies considered.
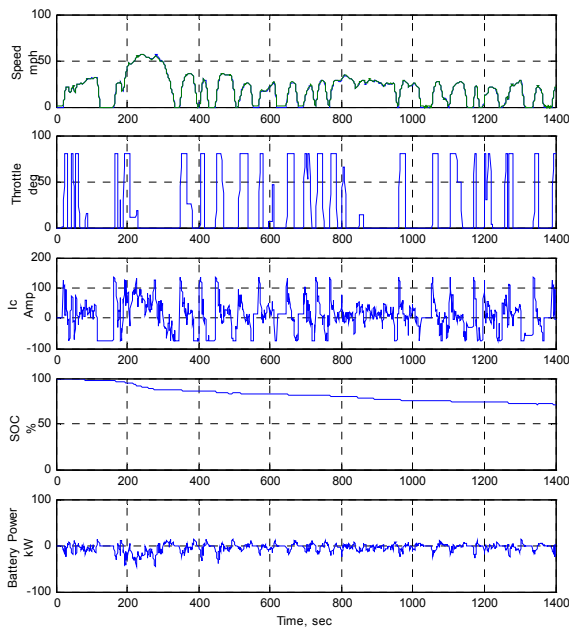
Figure 5. Performance results on the energy management strategy in between two extreme cases

Table 2. Fuzzy Torque Distribution Control performance results under FTP75 Urban drive cycle

	Fuel Economy (mpg)	DOD (%)	Emissions (g/mi)		
			CO	NOx	HC
Electrically Peaking	62.74	9.71	0.7278	0.4309	0.0671
Motor Assist	127.67	28.77	0.2651	0.1023	0.0393
ICE Peaking	∞	38.88	0	0	0

7. CONCLUSION

Torque distribution control for a parallel hybrid vehicle using fuzzy logic is tested to evaluate its performance under the FTP75 Urban driving cycle. For each energy management strategy, a different fuzzy rule set is used in the FTDC. The vehicle performance follows the fuzzy rule set describing the driver's preference. It is revealed that the vehicle performance, including the fuel economy (and emissions) and the battery state of charge (SOC) depends strongly on the energy management strategy deployed. In particular the so called electrically peaking strategy, while maintaining a high state of charge for the battery, results in acceptable but not very good fuel economy and emissions. On the other hand, the internal combustion engine peaking strategy results in excessive battery drainage and is not suitable in practice unless zero emissions is required. The most viable approach appears to be a charge

sustaining strategy that lies half way between the above strategies leading to good fuel economy and emissions. It is noted, however, that the present rule set results in somewhat higher than expected battery drainage with this approach. On the other hand, it is in principle possible to improve the battery recharge performance through fine tuning of the rule base used in the charge sustaining strategy. A still more viable approach, however, is to use the information obtained during the drive cycle to optimally switch between the aforementioned strategies. Such an approach, currently under investigation, is expected to produce both good fuel economy and acceptable battery discharge rate.

REFERENCES
[1] Buntin, D., 1994, "*Control System Design for a Parallel Hybrid Electric Vehicle*," M.S. thesis, Texas A&M University, College Station, TX.

[2] Jalil, N., Kheir, N. A., and Salman, M., 1997, "A Rule-Based Energy Management Strategy for a Series Hybrid Vehicle," *Proc.eedings of the American Control Conference*, pp. 889-893.

[3] Brahma, A., Glenn, B., Guezennec, B., Miller, T., Rizzoni, G., and Washigton, G., 1999, "Modeling, Performance Analysis and Control Design of a Hybrid Sport-Utility Vehicle," *Proceedings of IEEE International Conference on Control Applications*, pp. 448-453.

[4] Lee, H.-D., Koo, E.-S., Kim, S.-K., and Kim, J.-S., 1998, "Torque Control Strategy for a Parallel-Hybrid Vehicle Using Fuzzy Logic," *33rd IEEE Industrial Applications Society Annual Conference*, pp. 1715-1720.

[5] Farrall, S. D., and Jones, R. P., 1993, "Energy Management in an automotive electric/heat engine hybrid powrtrain using fuzzy decision making," *Proceedings of the International Symposium on Intelligent Control*, pp. 463-468.

[6] Available at *http://www.insightcentral.net*

Hybrid Vehicle Model Validation

**Validation Of Advisor Results
For Heavy Duty Buses**

Herbert Fox and Christos Efstathiou,
New York Institute of Technology

Presentation
Paper
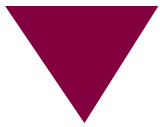
Benefits of Hybridization for Class 2B Trucks

Philip Sharer and Aymeric Rousseau,
Argonne National Laboratory

VALIDATION OF ADVISOR FOR HEAVY DUTY BUSES

Dr. Herbert Fox
Mr. Christos Efstathiou
New York Institute of Technology

Israel Ministry of Infrastructure
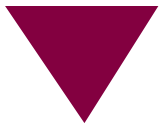
- Assess US use of alternative fuel vehicles for application to Israel
- Environmental benefits
- Economic issues
- Maintainability
- Fuel availability
- Cost factors

Purpose of ADVISOR study

- Validation of ADVISOR results
- Use of actual test data
- Compare to standard diesel vehicles
- Simulate, not buy, to evaluate new vehicles
- Predict enhancements to Israeli environment with alternative fueled vehicles --- mainly hybrid electric

Vehicles for which experimental data is available

Bus OEM	Chassis	Drive	Engine/ model year	After- treatment
NovaBUS	RTS	3 speed	DDC Series 50/1998	oxidation catalyst
Orion	VI	LMCS hybrid	DDC Series 30/1997 &1998	NETT particulate filter trap

Source: M.J. Bradley, DARPA NAVC1098-PG009837, February 2000

Bus cycles used in simulation

Central Business District Cycle

NY Composite Cycle
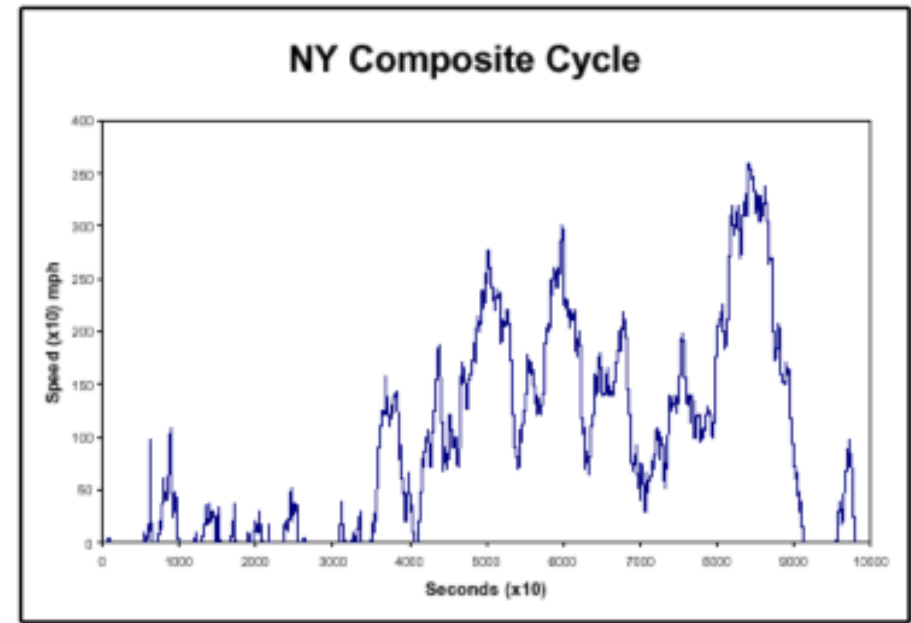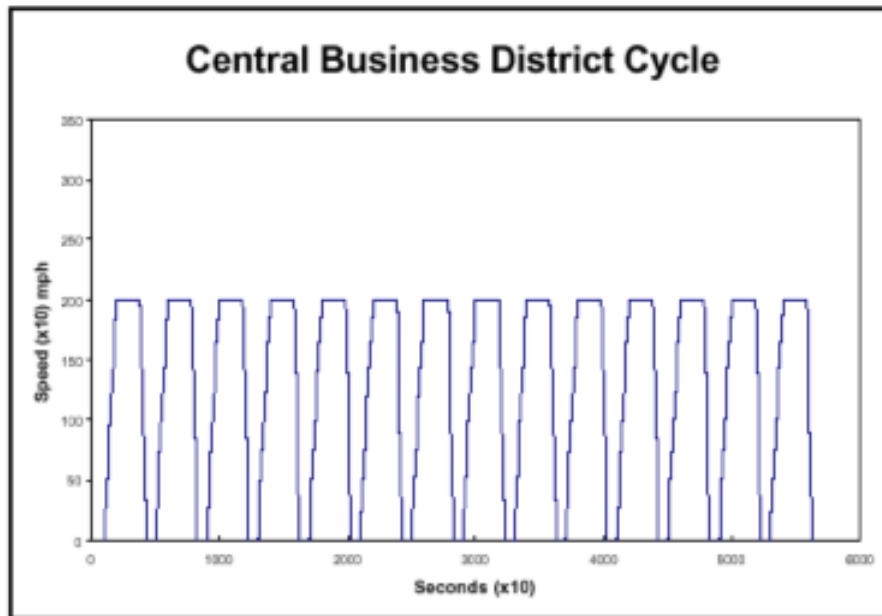
Some simulation notes

- "Naive" user point of view
- Three models for heavy duty buses
- Standard diesel from ADVISOR for fuel use
- Scaled standard diesel to model emissions
- Hybrid electric from ADVISOR without major modification

Standard diesel -- fuel use model

Standard diesel -- emissions model

Hybrid electric model

Validation -- standard diesel

CBD Cycle

NYC Composite

Validation -- hybrid electric

CBD Cycle

NYC Composite

Validation conclusions

- Fuel economy reasonably well modeled
- CO results are poor --- simulation errors not consistent
- Particulates not well-modeled
- HC (unburned hydrocarbons) well-modeled for hybrid, not for diesel
- NOx well-modeled for hybrid, not for diesel
- Overall, hybrid is reasonably well-modeled

Application to Israeli cities

- Tel Aviv much like New York; can apply results directly

- Jerusalem has many hills and there is a need to look at grade effects

CBD cycle --one peak / cycle

CBD cycle -- two peaks / cycle

Jerusalem simulation
CBD cycle / Hybrid electric bus

Maximum height 65 ft

■ 0% grade ■ Single □ Double

Maximum height 130 ft

■ 0% grade ■ Single □ Double

Jerusalem simulation
NY Composite / Hybrid electric bus

Maximum height 75 ft

■ 0% grade ■ Single □ Double

Maximum height 150 ft

■ 0% grade ■ Single □ Double

Overall conclusions

- **Overall trends predicted by ADVISOR are correct when comparing heavy duty vehicles over any given cycle**
- **Clear need to develop better engine maps for heavy duty vehicles**
- **Catalytic converter performance and interaction with other emissions needs to be reviewed**
- **Other fuels --- low sulfur diesel, synthetic diesel, CNG, LNG --- would be useful to have**
- **Easier representations of grade would be useful**

VALIDATION OF ADVISOR RESULTS FOR HEAVY DUTY BUSES[1]

by

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ABSTRACT

The overarching purpose of our project is to assess the status of alternative fuel technologies to see which are applicable, in general, to the Israeli market and, in particular, to the major cities in Israel. We need to evaluate these technologies in the Israeli environment and duty cycles so that adequate prediction of performance can be obtained. Clearly, the best way to do so, short of purchasing and testing vehicles, is through simulation.

This paper presents results from a study comparing experimental results for heavy duty buses to the output from the application of ADVISOR. In particular we looked at fuel economy, carbon monoxide emissions, particulate matter emissions, nitrous oxide emissions to see how well ADVISOR can predict vehicle performance. This is critically important when we use ADVISOR to design and implement new bus technologies or apply them to cities looking to invest in environmentally friendly systems.

We modeled standard heavy duty and hybrid buses operating over well-known duty cycles, i.e., the CBD cycle and the New York Composite Cycle, and used recent experimental data for comparison. Our results show that:

[2] Person to whom correspondence should be addressed. Telephone 516 686 7895; email **herb@nyit.edu**

▸ Fuel economy is well modeled.
▸ For the standard diesel, CO results are poor; there is a significant understatement of these emissions. For the hybrid case, experimental emissions are about half those of ADVISOR. The errors between the vehicles are in different directions: the standard diesel underpredicts, the hybrid overpredicts.
▸ Particulates are not modeled well for either vehicle on either cycle.
▸ Unburned hydrocarbons (HC) are reasonably well modeled by ADVISOR. This is particularly true for the hybrid.
▸ NOx is very well modeled.

This suggests the following for the use of ADVISOR:

▸ We believe that ADVISOR can safely and adequately be used to predict trends when comparing different buses.
▸ There is a clear need to develop new engine maps for heavy duty vehicles accounting for emissions.
▸ What was so surprising is the relatively poor modeling of particulate matter. It seems to us that there is a need to review the performance of the catalytic converter routines and their interaction with engine emissions to better model these systems.
▸ Given the trend to a variety of alternative fuels—low sulfur diesel, CNG, LNG—it would be useful to have these maps available as choices.

Finally we did simluate some cities in Israel to investigate trends. This assures us that ADVISOR can reasonably be applied to these vehicles in this environment.

1. INTRODUCTION

In many countries world-wide, there is a growing interest in the use of alternative fueled buses. This is especially true in those cities where environmental issues are coming to the fore and where there are older and historic buildings adversely affected by emissions. The purpose of our overarching project is to assess the status of alternative fuel technologies to see which are applicable, in general, to the Israeli market and, in particular, to the major cities in Israel.

Our goal is to look at the current status of the results from testing of existing fleets of alternative fueled vehicles now on-going in the United States to assess outcomes and see if the vehicles can effectively be employed in Israel. In particular we are studying the following issues:

- ▸ environmental benefits (emissions of particulates, NO_x, CO/CO_2, unburned hydrocarbons)
- ▸ economic benefits
- ▸ ability to integrate new systems into existing fleets
- ▸ maintainability of the new systems
- ▸ fuel availability, as applicable
- ▸ safety issues - maintenance and personnel
- ▸ passenger comfort and desirability (for example, low floor vs. high floor vehicles)
- ▸ duty cycle consequences
- ▸ vehicle cost factors
- ▸ potential return on investment

Technologies we assess are those that have had rigorous evaluations so that a real data base can be developed for use in Israel. In addition we will need to evaluate these technologies in the Israeli environment and duty cycles so that adequate prediction of performance can be obtained. Clearly, the best way to do so, short of purchasing vehicles, is through simulation.

There is a concomitant need to validate any simulation software so that reasonable recommendations can be made[3]. The purpose of this paper, then, is to test ADVISOR and compare its results to those experimental data in the published literature. By doing so we can see where ADVISOR works and where it does not and then suggest means to update the software so that improvements can be made.

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[3] Indeed at the last ADVISOR conference in August 2000, this was one of the points made concerning the applicability of this software.

2. BASIC INFORMATION

In this study we take the point of view of the naive user. This is one who comes to ADVISOR and wishes to apply it directly without burrowing into the details of MatLab files or the simulation itself. That is, we wish to simply apply ADVISOR to current experimental results, evaluate the results and then see if they can be used to predict performance directly or just predict trends qualitatively.

The source of test data for this effort comes from a detailed experimental effort to measure bus performance and emissions[4]. The Northeast Advanced Vehicle Consortium initiated the testing of hybrid-electric buses to demonstrate the energy efficiency and emission performance of "State of the Art" hybrid-electric heavy-duty vehicles with respect to late model conventional diesel heavy-duty vehicles and alternative fuel CNG buses. An independent team of engineers and scientists facilitated the evaluation consisting of personnel from M.J. Bradley & Associates and West Virginia University. Project participants included transit operators from Boston, Massachusetts and New York City who own and operate the buses. Several original equipment bus manufacturers, engine manufacturers and hybrid drive system manufacturers were on hand to assure that the testing was uniformly conducted and reviewed.

Emissions measured over a variety of driving cycles included: nitrogen oxides, carbon monoxide, carbon dioxide, organic compounds and particulate matter. Fuel economy for each vehicle was also determined.

For the study presented here, two buses were simulated to compare to the data from the Bradley report. Exhibit 1 summaries the basic characteristics of these buses:

Exhibit 1
Forty-foot buses tested

Bus OEM	Bus Chassis	Drive	Engine / Model year	After-treatment
NovaBUS	RTS	3 speed	DDC Series 50 / 1998	Oxidation catalyst
Orion	VI	LMCS hybrid	DDC Series 30 / 1997 & 1998	NETT particulate filter trap

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[4] See M.J. Bradley & Associates, Inc., "Hybrid-Electric Drive Heavy=Duty Vehicle Testing Program, Final Emissions Report," prepared for Defense Advanced Research Projects Agency, NAVC1098-PG009837, February 15, 2000.

The testing encompassed several different bus cycles. Those relevant to our study are shown in Exhibits 2 and 3 and discussed briefly below.

The central business district (CBD), which appeared as the Society of Automotive Engineers (SAE) recommended practice J1376, is commonly used to evaluate transit buses; it is included as one the many driving cycles available from within ADVISOR. The CBD cycle (see Exhibit 2) is typically used to evaluate transit buses and is made up of 14 identical sections containing an acceleration to 20 mph, a cruise at 20 mph, braking to a stop, then dwell. The total cycle covers 2.0 miles over 600 seconds. While the CBD cycle is repeatable from a driver in the loop standpoint, it has several drawbacks. The acceleration rate is fixed which tends to favor buses with five speed transmissions and larger engines. The cycle is dominated by the 20-mph cruise, which penalizes buses that are not geared for optimum efficiency at that particular speed. The deceleration from 20-mph is twice as fast as the acceleration to 20-mph, 4.5 seconds versus 9 seconds, which is not typical of actual in-use driving. The average speed for the CBD cycle is 12.6 mph, generally faster than that observed by most transit operations.

As a consequence and despite its adoption by the SAE, this test cycle often does not seem to accurately reflect actual service routes in many transit districts. Therefore, another cycle was used in this study, for which experimental results are also available. The New York City Composite cycle, also available with ADVISOR, (see Exhibit 3) comprises acceleration and deceleration rates over a wider range of variation than the CBD. The NY Composite cycle represents a mix of inner city and urban transit bus use that allows for the bus to reach and sustain greater speeds. The average speed of the NY Composite cycle is 8.8 mph. It may be noted that it is an extremely difficult cycle for both the driver and the bus itself to follow accurately due to the large number of rapid speed changes (indeed we found that as well in the ADVISOR results). Buses that are powerful enough to follow the cycle are penalized by following a difficult cycle while less powerful buses effectively cheat the cycle, getting better fuel economy as a result.

In any case most transit operators would suggest that actual operations (and thereby performance) likely lies between the Composite and the CBD. For design purposes, then, these are useful for our validation, and by extension, for our prediction study.

Exhibit 2
CBD Bus Cycle

Central Business District Cycle
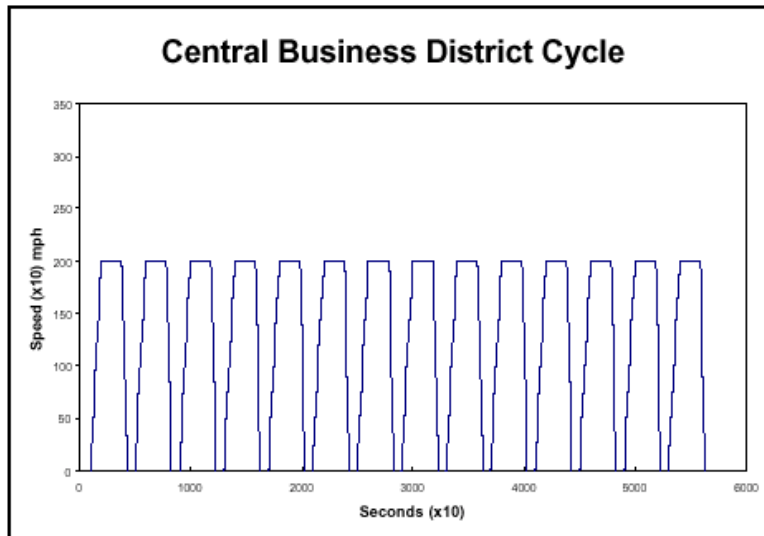
Exhibit 3
NY Composite Bus Cycle

NY Composite Cycle
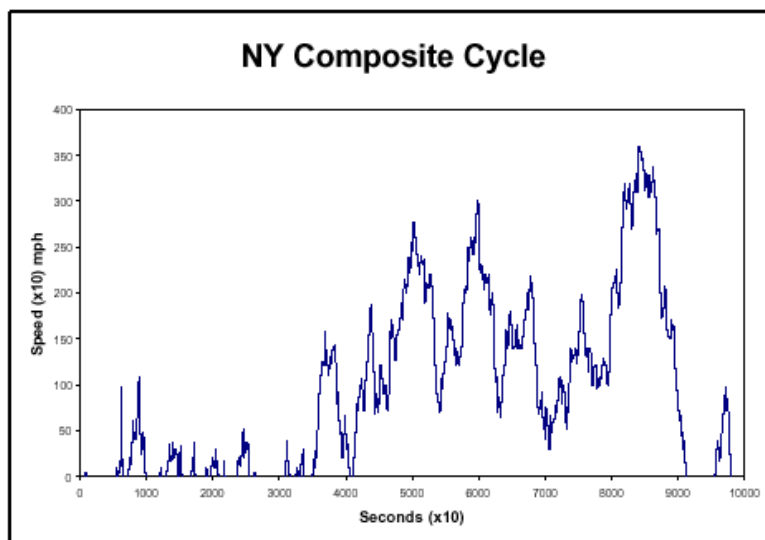
3. SIMULATION RESULTS

Now we turn to the application of ADVISOR. Perhaps the easiest way to see our input data (again from the point of view of the naive user) is to look at ADVISOR displays directly. Note that we use three configurations for comparative purposes. The first (Exhibit 4) is used to predict fuel consumption for the standard diesel. Unfortunately the engine map from ADVISOR does not provide emissions data. We developed a second, with a scaled up engine, to use for the emissions validations (Exhibit 5). The last is a hybrid electric (Exhibit 6). All employed catalytic converters with appropriate power train controls. Note also that each case was run for four complete cycles.

Numerical results are shown in Exhibits 7 and 8, for the standard diesel and the hybrid, respectively; graphic displays of this data are presented in Exhibits 9 and 10. Note that each displays the data separately for the CBD cycle and for the New York Composite cycle. For performance and emissions, inspection of these results suggests the following:

▸   Fuel economy is well modeled. Comparative results indicate at worst a 14% difference between ADVISOR and the experiments.

▸   For the standard diesel, CO results are poor; there is a significant difference from the experimental results (between -90% to 105%). For the hybrid case, experimental emissions are about half those of ADVISOR. Note that errors between the vehicles are in different directions: the standard diesel underpredicts, the hybrid overpredicts.

▸   Particulates are not modeled well for either vehicle on either cycle, with large errors ranging from 61% to 232%.

▸   Unburned hydrocarbons (HC) are reasonably well modeled by ADVISOR for the hybrid, not so for the standard diesel.

▸   NOx is very well modeled for the hybrid but are not as good for the standard diesel.

This suggests the following for the use of ADVISOR:

▸   We believe that ADVISOR can safely and adequately be used to predict trends when comparing different buses. The trends shown in Exhibits 7 - 10 bear this out. As we move to the more complex cycles, the emissions change in ways that are surely expected.

Exhibit 4
Standard diesel — fuel use model

Exhibit 5
Standard diesel — emissions model

Exhibit 6
Hybrid electric model

Vehicle Input

Component: fuel_convert

Plot Selection: fc_efficiency

Fuel Converter Operation
Mercedes 1.7L Diesel Engine f/ ORNL

Exhibit 7
Standard Diesel
Comparison between ADVISOR and Test Results

	CBD Cycle			NYC Composite Cycle		
Parameter	ADVISOR	Test	Percent error	ADVISOR	Test	Percent error
Fuel use (mpg)	4.0	3.5	14.3%	3.3	3.0	10%
CO (grams/mile	0.58	3.0	-80.7%	0.712	7.0	-89.8%
PM (grams/mile	0.857	0.24	257%	0.74	0.46	60.9%
HC (grams/mile	0.219	0.14	56.4%	0.305	0.22	38.6%
NOx (grams/mile)	47.535	30.1	57.9%	35.815	31.5	13.7%

Exhibit 8
Hybrid Electric
Comparison between ADVISOR and Test Results

	CBD Cycle			NYC Composite Cycle		
Parameter	ADVISOR	Test	Percent error	ADVISOR	Test	Percent error
Fuel use (mpg)	4.6	4.3	7.0%	3.8	4.2	-9.5%
CO (grams/mile	0.205	0.1	105%	0.406	0.2	103%
PM (grams/mile	0.287	0.12	139%	0.465	0.14	232%
HC (grams/mile	0.083	0.08	3.8%	0.175	0.38	-54%
NOx (grams/mile)	18.179	19.2	-5.3%	18.614	19.9	-6.5%

Exhibit 9
Performance and Emissions Validation
Standard Diesel

CBD Cycle

NYC Composite
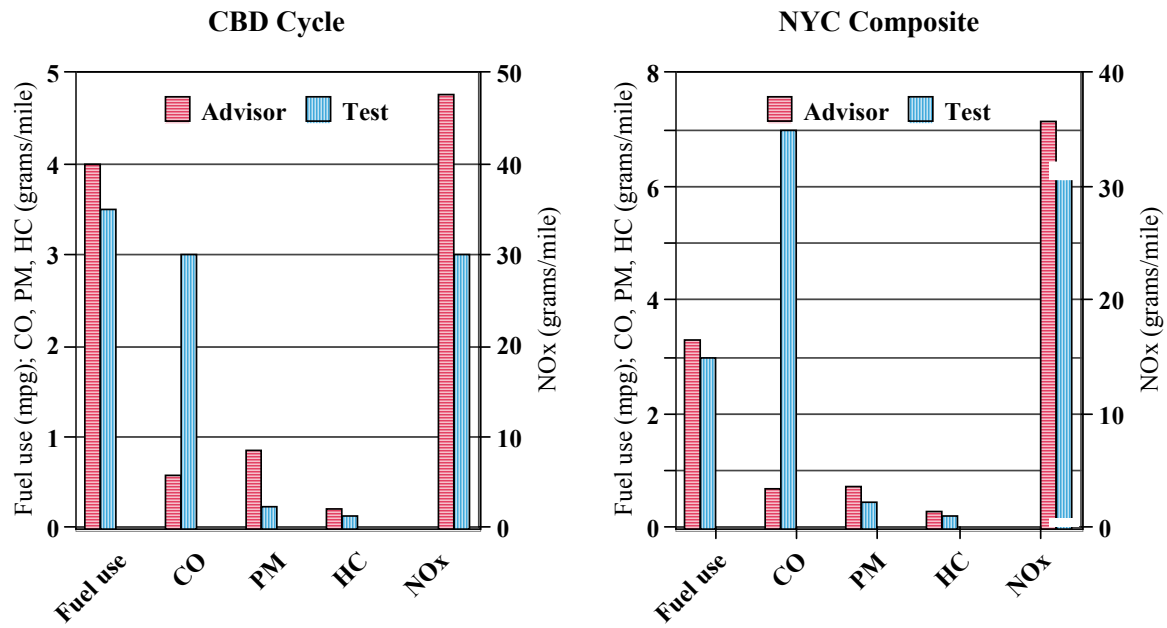
Exhibit 10
Performance and Emissions Validation
Hybrid Electric
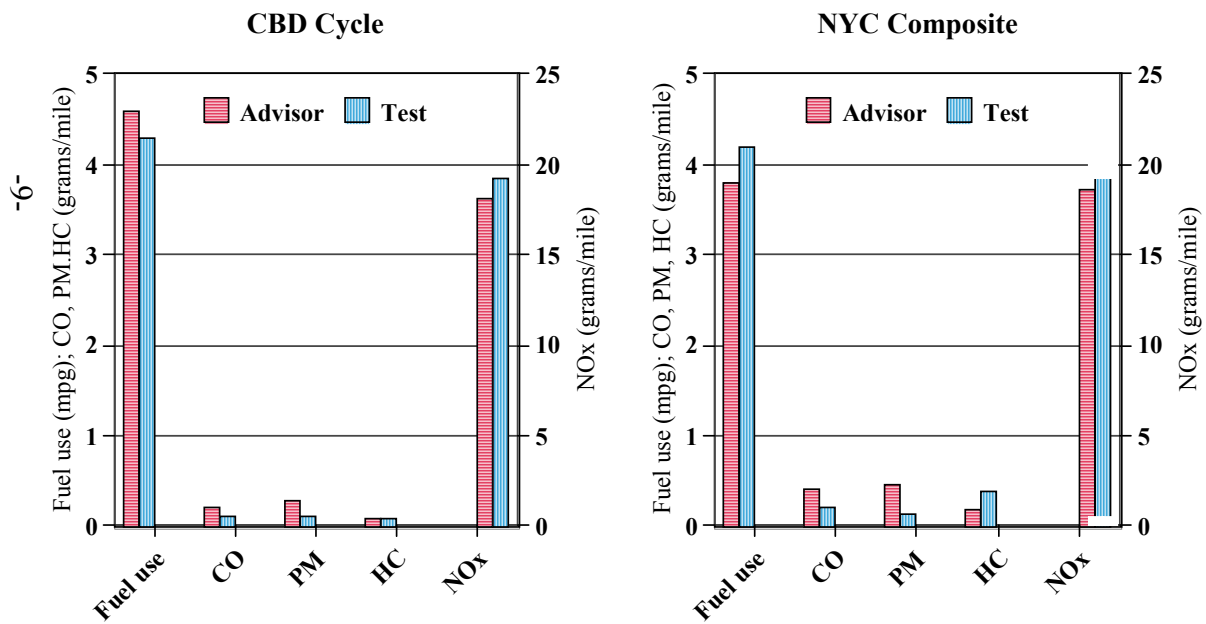
CBD Cycle

NYC Composite

▸ There is a clear need to develop new engine maps for heavy duty vehicles accounting for emissions. We recognize the difficulty in doing to and encourage the ADVISOR user community to assist in this regard.

▸ What was so surprising is the relatively poor modeling of particulate matter. It seems to us that there is a need to review the performance of the catalytic converter routines and their interaction with engine emissions to better model these systems.

▸ Given the trend to a variety of alternative fuels—low sulfur diesel, CNG, LNG—it would be useful to have these maps available as choices.

4. APPLICATION TO ISRAELIS CITIES

Finally we return to the original motivation for this effort and look at some results that may be considered typical of the major cities in Israel, Tel Aviv and Jerusalem. For the former, given its location on the Mediterranean, it would appear to be adequately modeled with the cycles shown earlier. And the trends developed there can be safely used for evaluating buses for them.

Jerusalem presents a different picture. Here grade is critical because of the nature of the topography and typical bus routes. For our purposes, in this preliminary assessment and to develop trend information, we present some data with the New York Composite cycle and the hybrid electric vehicle. We used two types of grade input. The first is a constant grade of 2% (available from within ADVISOR itself); the second is a variable grade shown in Exhibit 11 and developed by us. Comparative emissions and fuel use are shown in Exhibit 12, using the results from Exhibits 9 and 10 as the base. As might be expected, the effect of grade is considerable and bears heavily on choices for vehicles.

To further explore what happens in a city like Jerusalem with its many hills, we modified the grade component of both the cycles discussed earlier. Reference should be made to Exhibits 13 and 14 where grade versus distance is shown for the CBD cycle. Two basic cases were modeled: In the first (Exhibit 13), there is a single peak for the cycle; in the second (Exhibit 14), we modeled a typical ride up and down two hills in the two or so miles for the cycle. In addition we also doubled the maximum elevation driven. This gave us a set of four runs for comparison purposes. And although not shown here, the same four cases were introduced to the New York Composite Cycle.

Results for the hybrid electric bus are provided in Exhibits 15 and 16 for the CBD and Composite Cycles respectively. Fuel economy and emissions results are what might be expected and lead again to the suggestion that, at least qualitatively, ADVISOR provides appropriate trend information for evaluating bus performance and can suggest the advantages of selecting one type of vehicle over another.

Exhibit 11
Variable Grade Model

Exhibit 12
Simulation of Grade Effects
Hybrid Electric Vehicle

New York Composite Cycle
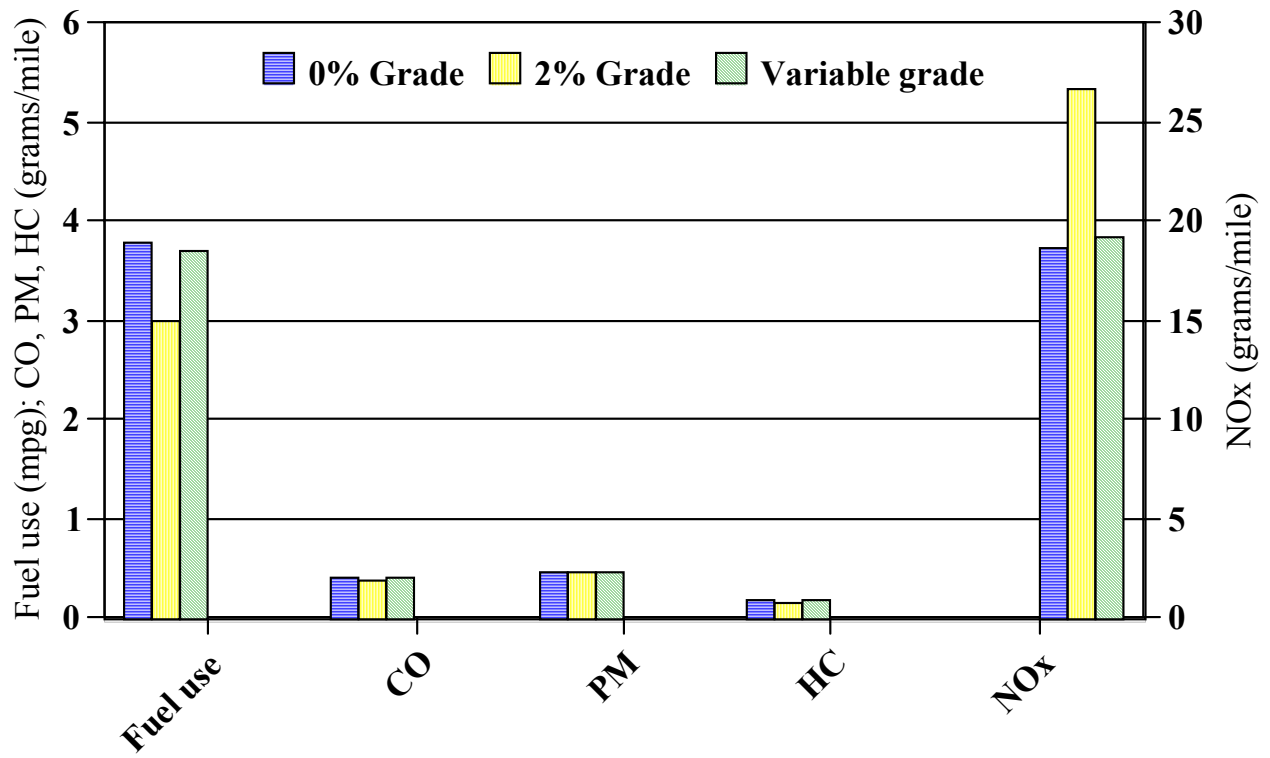
Exhibit 13
CBD Cycle
One peak in each cycle

CYC_CBDBUS2
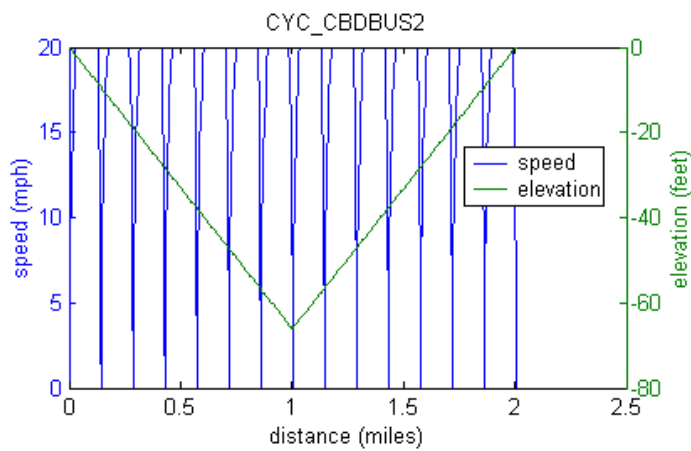
Speed/Elevation vs. Distance

○ Description   ● Statistics

CYC_CBDBUS2
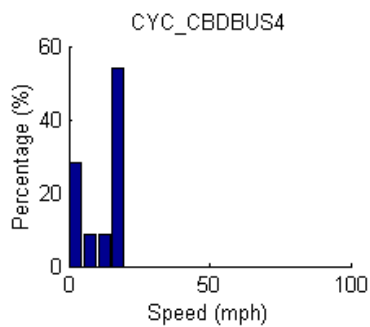
time:	574 s
distance:	2.01 miles
max speed:	20 mph
avg speed:	12.58 mph
max accel:	3.37 ft/s^2
max decel:	-6.89 ft/s^2
avg accel:	2.67 ft/s^2
avg decel:	-5.48 ft/s^2
idle time:	115 s
no. of stops:	14
max up grade:	1.3 %
avg up grade:	1.2 %
max dn grade:	1.3 %
avg dn grade:	1.2 %

● Drive Cycle   CYC_CBDBUS2 ▼
  Trip Builder

Time Step 1   # of cycles 4
☐ SOC Correction   ☐ Cycle Filter

                    Initial Conditions

☐ Constant Road Grade
☐ Interactive Simulatic

○ Multiple Cycles   none ▼

○ Test Procedure   TEST_CITY_HWY ▼

Additional Tests
☐ Acceleration Test   Accel Options
☐ Gradeability Test at   Grade Options

☐ Parametric Study   # of variables 1 ▼

	Low	High	# Pts
Variable 1			
veh_mass ▼	15940	16340	3
Variable 2			
veh_CD ▼	0.79	0.99	3
Variable 3			
veh_FA ▼	8.0516	10.0516	3

Load Sim. Setup   Save   Help
Optimize cs vars   Back   RUN

Exhibit 14
CBD Cycle
Two peaks in each cycle

Exhibit 15
CBD Results

Approximate maximum elevation (feet)	Number of grades per cycle	Fuel use (mpg)	HC (grams/mile)	CO (grams/mile)	NOx (grams/mile)	PM (grams/mile)
0	0	4.6	0.083	0.205	18.179	0.287
65	1	4.3	0.087	0.212	19.133	0.295
65	2	3.8	0.085	0.216	22.704	0.299
130	1	3.9	0.088	0.220	22.142	0.302
130	2	3.7	0.090	0.226	23.324	0.305

Exhibit 16
New York Composite Cycle Results

Approximate maximum elevation (feet)	Number of grades per cycle	Fuel use (mpg)	HC (grams/mile)	CO (grams/mile)	NOx (grams/mile)	PM (grams/mile)
0	0	3.8	0.175	0.406	18.614	0.465
75	1	3.7	0.179	0.415	18.927	0.468
75	2	3.6	0.185	0.427	19.552	0.472
150	1	3.5	0.187	0.423	20.157	0.472
150	2	3.4	0.192	0.445	20.879	0.482

Exhibit 17
Jerusalem Simulation
Hybrid Electric Bus / CBD Cycle
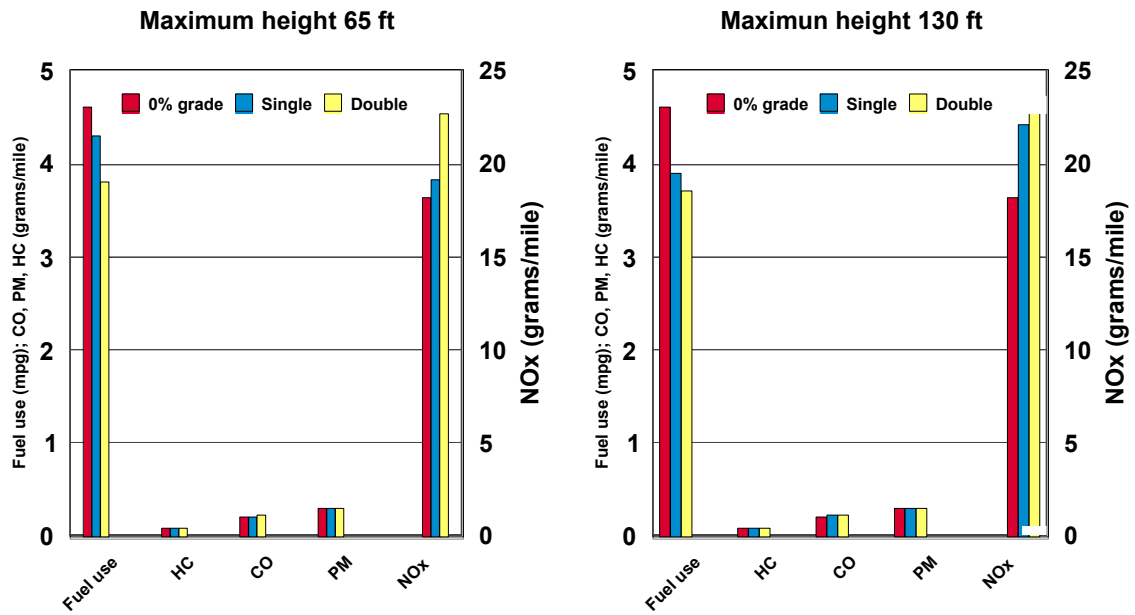
Exhibit 18
Jerusalem Simulation
Hybrid Electric Bus / NY Composite

Maximum height 75 ft

Maiximum height 150 ft
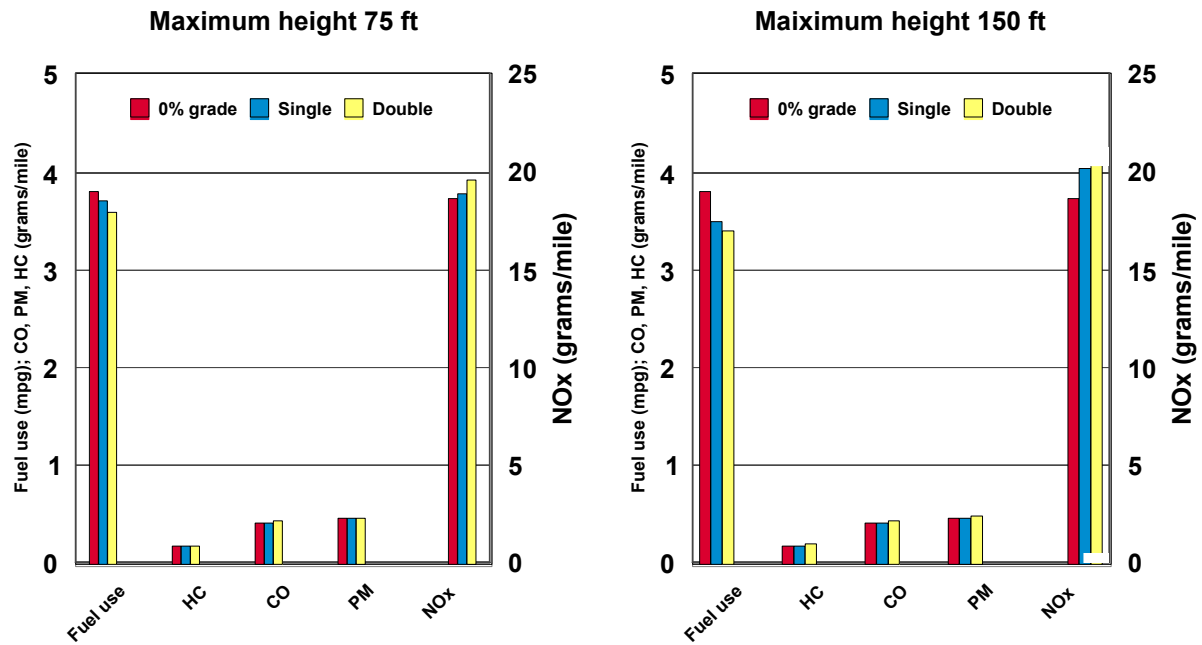
5. OVERALL CONCLUSIONS

Based on the results provided, we summarize our conclusions in this final section. First on an overall basis, ADVISOR adequately represents correct trends when comparing heavy duty vehicles over any given cycle. However, while the trends are correct, ADVISOR is not really successful in predicting levels of emissions, especially for standard large buses. ADVISOR does provide reasonable results for hybrid vehicles, except for particulates. That is likely due to the greater attention paid to emissions in these cases, although models of catalytic converters do not appear up to the task.

For future releases of ADVISOR, we would recommend the following:

▸ There is a clear need to develop new engine maps for heavy duty vehicles accounting for emissions.

▸ What was so surprising is the relatively poor modeling of particulate matter. It seems to us that there is a need to review the performance of the catalytic converter routines and their interaction with engine emissions to better model these systems.

▸ Given the trend to a variety of alternative fuels—low sulfur diesel, synthetic diesel, CNG, LNG—it would be useful to have these maps available as choices.

▸ Finally better representations of grade in the driving cycles would be helpful to those of us who have need for modeling in difficult physical terrain.

Benefits of Hybridization for Class 2B Trucks

Phillip Sharer
Aymeric Rousseau

1

➤ Silverado 1500 Pickup Truck (Class 2A) Validation

➤ Extension to Silverado Pickup Truck (Class 2B) Validation

➤ Effect of 21st Century Truck Loss Goals

➤ Effect of Dieselization

➤ Effect of Hybridization

➤ Conclusions

➢ Used GM Loss Data from Truck and Bus 2000 Presentation for

- MY2000 4WD Silverado 1500 Pickup

- Class 2A

- 5.3L V8 285 hp Spark-Ignition Engine

- 4 speed Automatic Transmission

3

TRANSPORTATION
TECHNOLOGY R&D CENTER
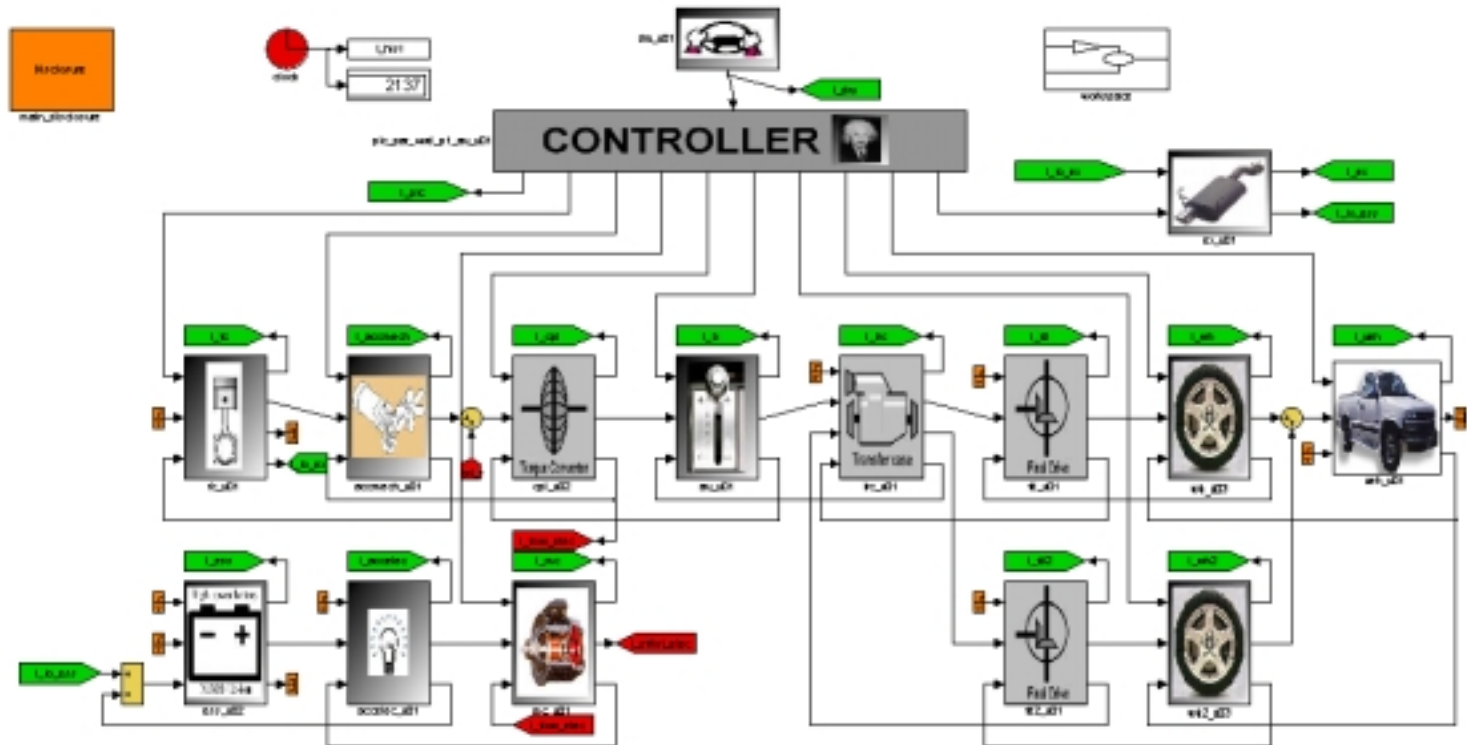
2000 4WD Silverado 1500 EPA Combined Cycle Energy Losses

Total Fuel Energy	56277 kJ
Engine Losses	40973 kJ
Mechanical Accessories	1391 kJ
Transmission Losses	2202 kJ
Transfer Case and Driveline Losses	2063 kJ
Final Drive Losses	672 kJ
Brake Drag	287 kJ
Rolling Resistance	1726 kJ
Aerodynamic Drag	4849 kJ
Vehicle Deceleration	2114 kJ

5

GM Truck Group data

Engine Losses Are Validated To Within 5% For The Silverado 1500 (Class 2A)

EPA Combined Fuel Energy (GM)	EPA Combined Fuel Energy (ANL)	Relative Error
56277kJ ( )	56261kJ ( )	< 1%
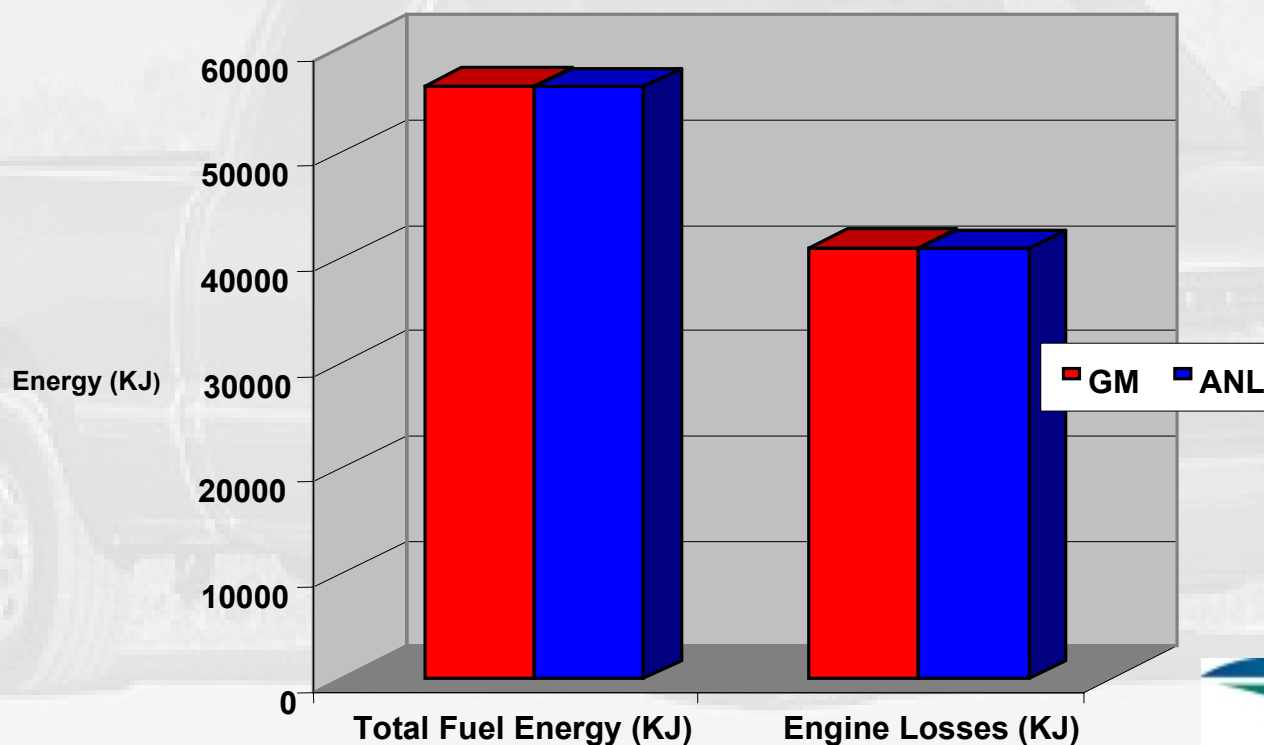
Single Component Drivetrain Losses Are Validated To Within 5%

Comparison of Drivetrain Losses
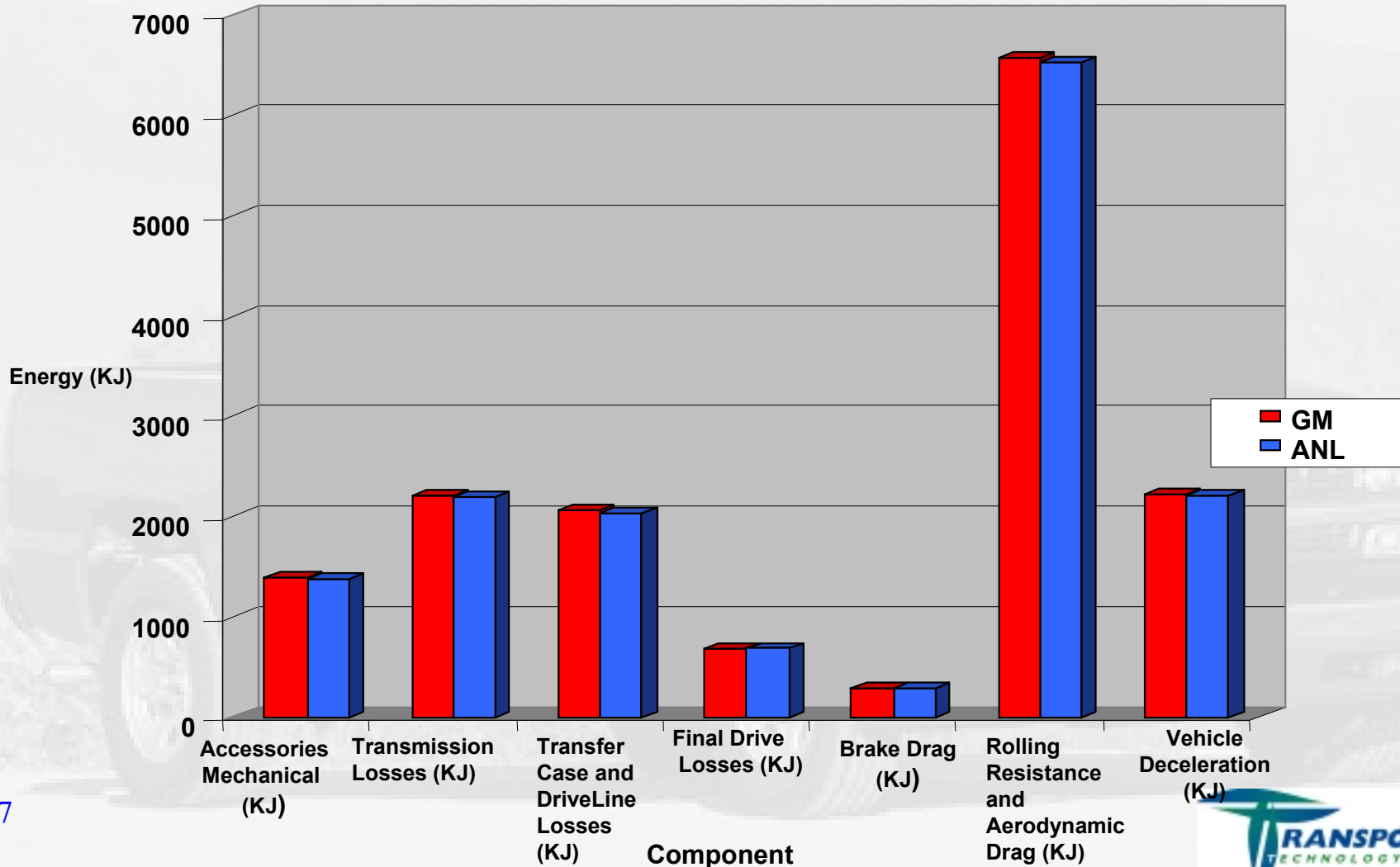
➤ Conventional Class 2B

➤ Conventional Class 2B Using 21st Century Truck Losses

➤ Conventional Class 2B Using 21st Century Truck Losses and 20% Reduced Mass

➤ Hybrid Class 2B Using 21st Century Truck Losses and 20% Reduced Mass

➤ Combined EPA Cycle (CAFE)

➢ Predicted Class 2B Fuel Economy Using Class 2A Results

- Changed Vehicle Mass to Reflect Class 2B Heavier Frame, Suspension and Axles
- Used Same
  - 5.3L SI Engine
  - 4-Speed Automatic Transmission
  - Transfer Case
  - Final Drive

9
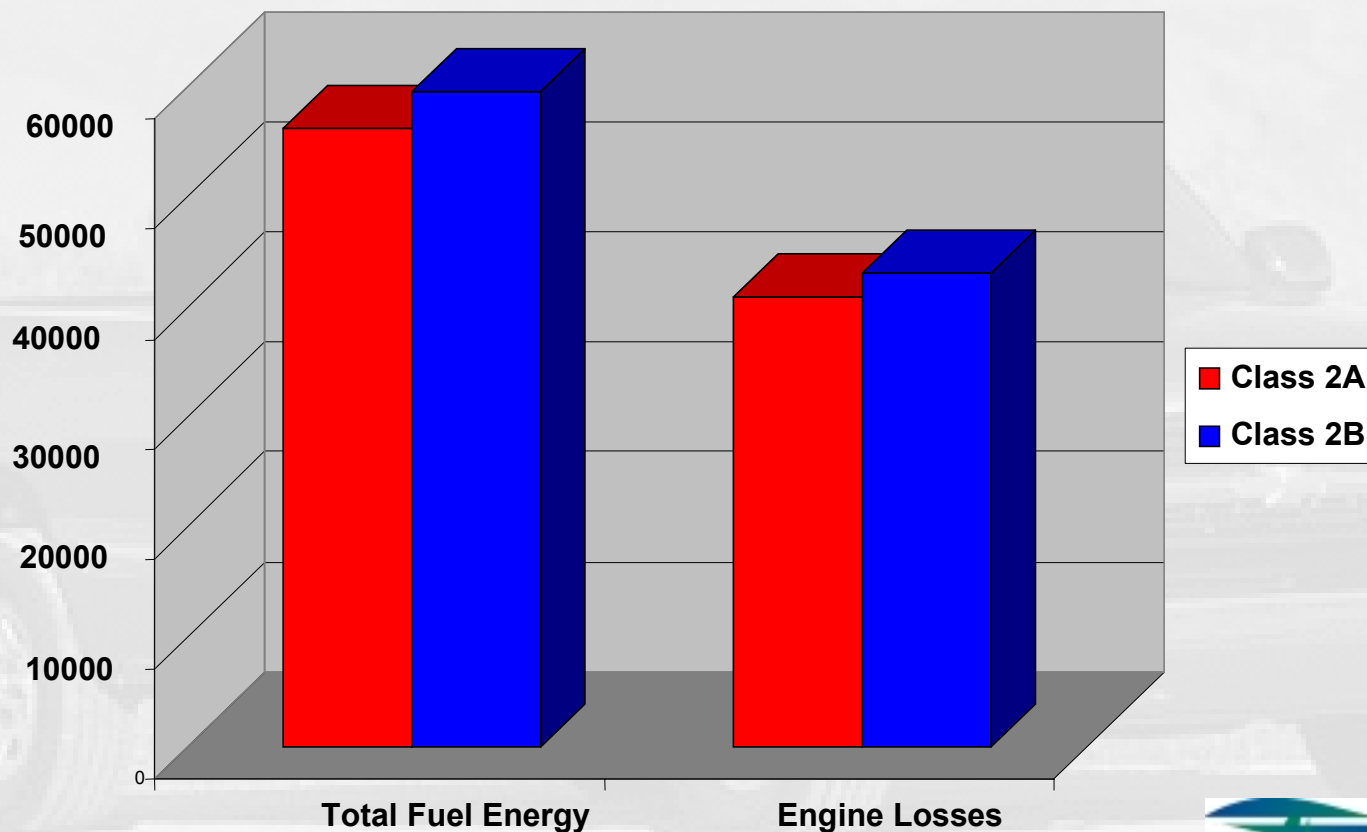
Component Losses Are Increased Due to Increased Vehicle Mass
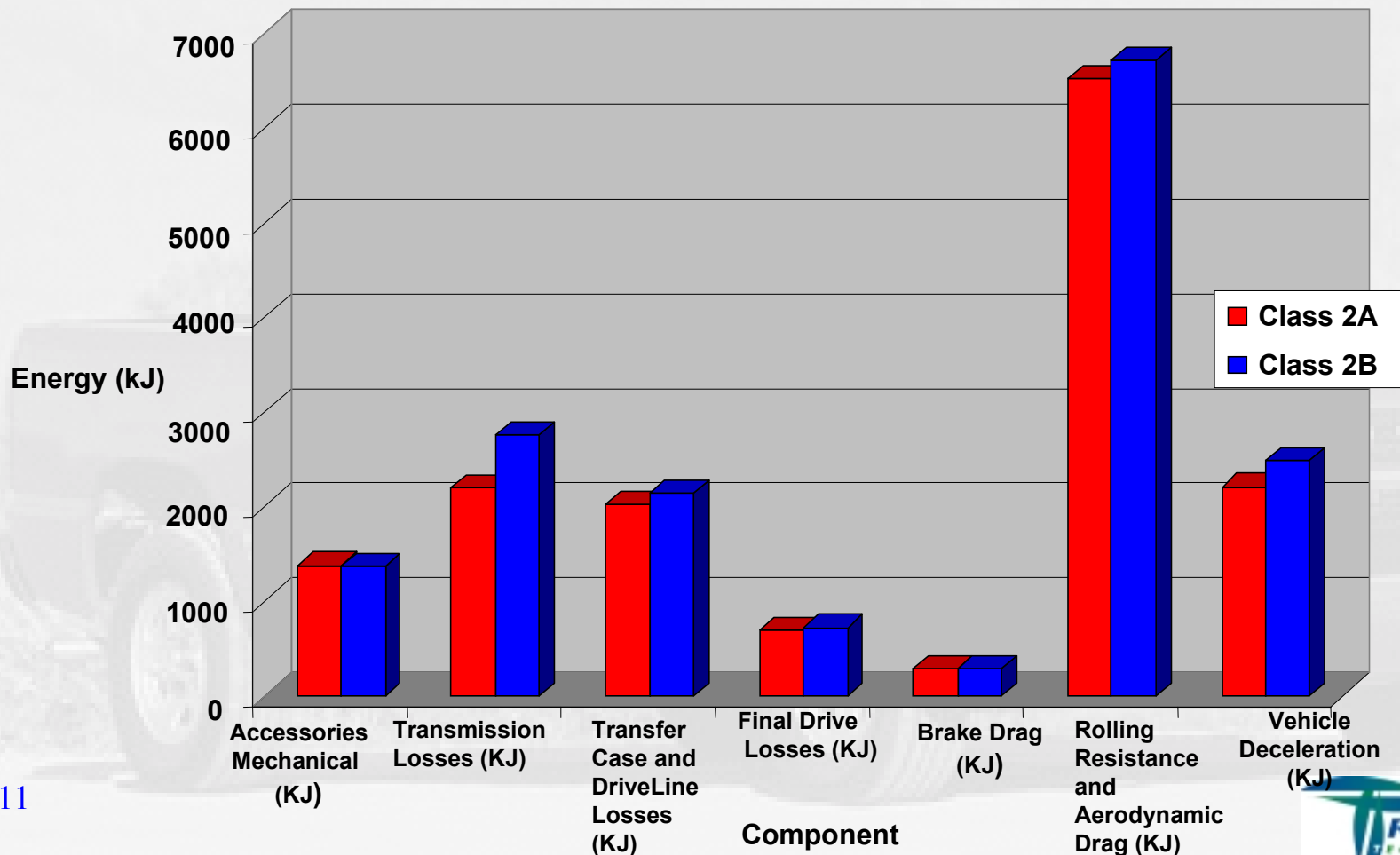
Component Losses Are Increased On Average By 7%

Class 2B Energy Results	ANL Class 2A Losses	ANL Class 2B Losses	Increase In Losses
Total Fuel Energy	56261 kJ	59619 kJ	6%
Engine Losses	40898 kJ	43077 kJ	5%
Mechanical Accessories	1375 kJ	1369 kJ	-0.4%
Transmission Losses	2195 kJ	2759 kJ	26%*
Transfer Case and Driveline Losses	2027 kJ	2134 kJ	5%
Final Drive Losses	685 kJ	721 kJ	5%
Brake Drag	285 kJ	285 kJ	0%
Rolling and Aerodynamic	6526 kJ	6719 kJ	3%
Vehicle Deceleration	2205 kJ	2489 kJ	13%

* Heavier torque converter duty cycle

12

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Drivetrain Component	Baseline Class 2B Losses	Reduction Goal	Class 2B Reduced and Propagated Losses
Accessories	1369 kJ	-35%	871 kJ
Transmission Losses	2759 kJ	-20%	1935 kJ
Transfer Case and Driveline Losses	2134 kJ	-20%	1420 kJ
Final Drive Losses	721 kJ	-20%	531 kJ
Brake Drag	285 kJ	-20%	243 kJ
Aerodynamic Drag and Rolling Resistance	6719 kJ	-20%	5393 kJ

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Impact of 21st Century Truck Loss Reduction Targets

EPA Combined Fuel Economy | 21.8 mpg

Class 2B Reduced and Propagated Losses Compared to Baseline Class 2B

14
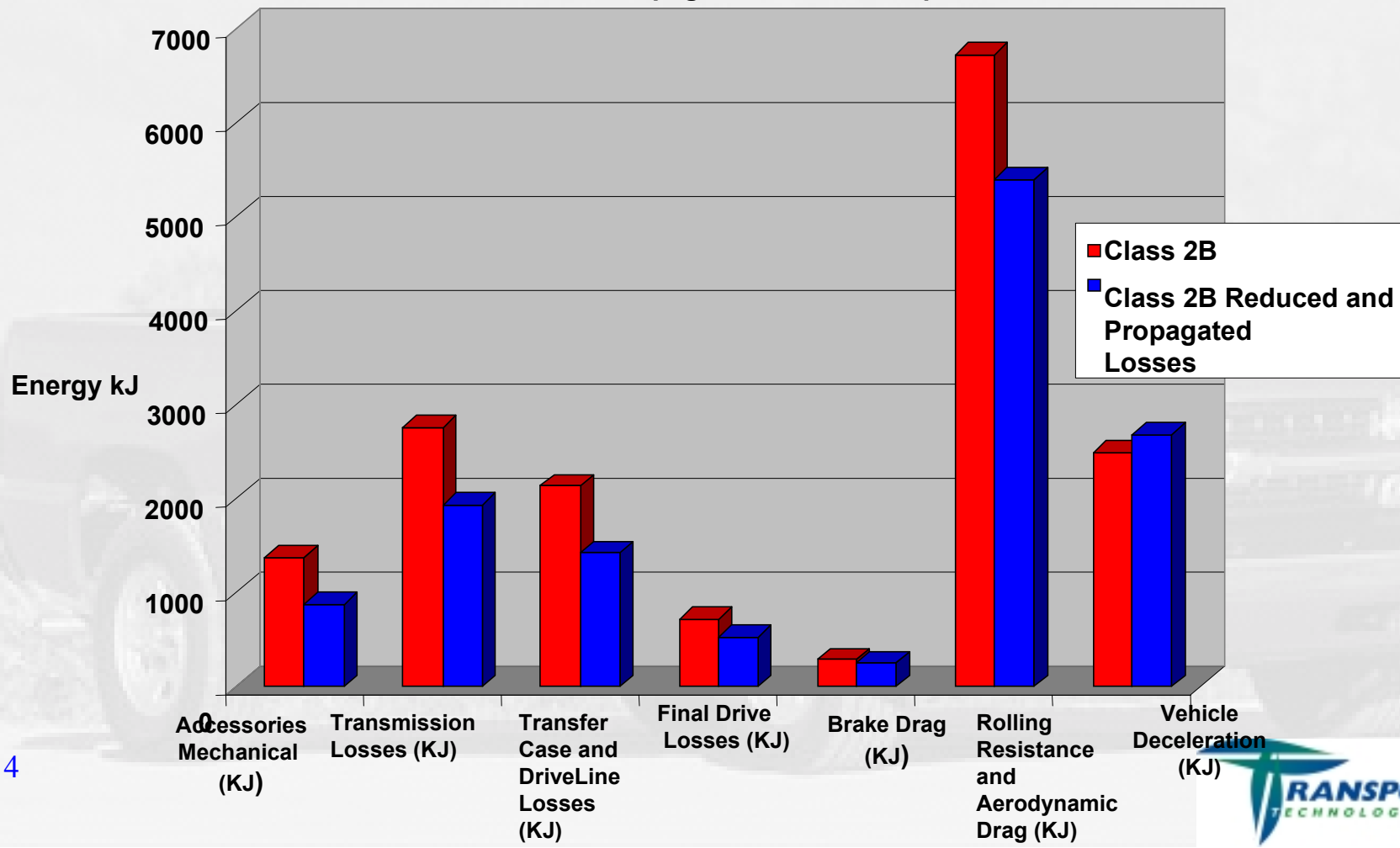
Additional Impact of 20% Mass Reduction

EPA Combined Fuel Economy	23.6 mpg
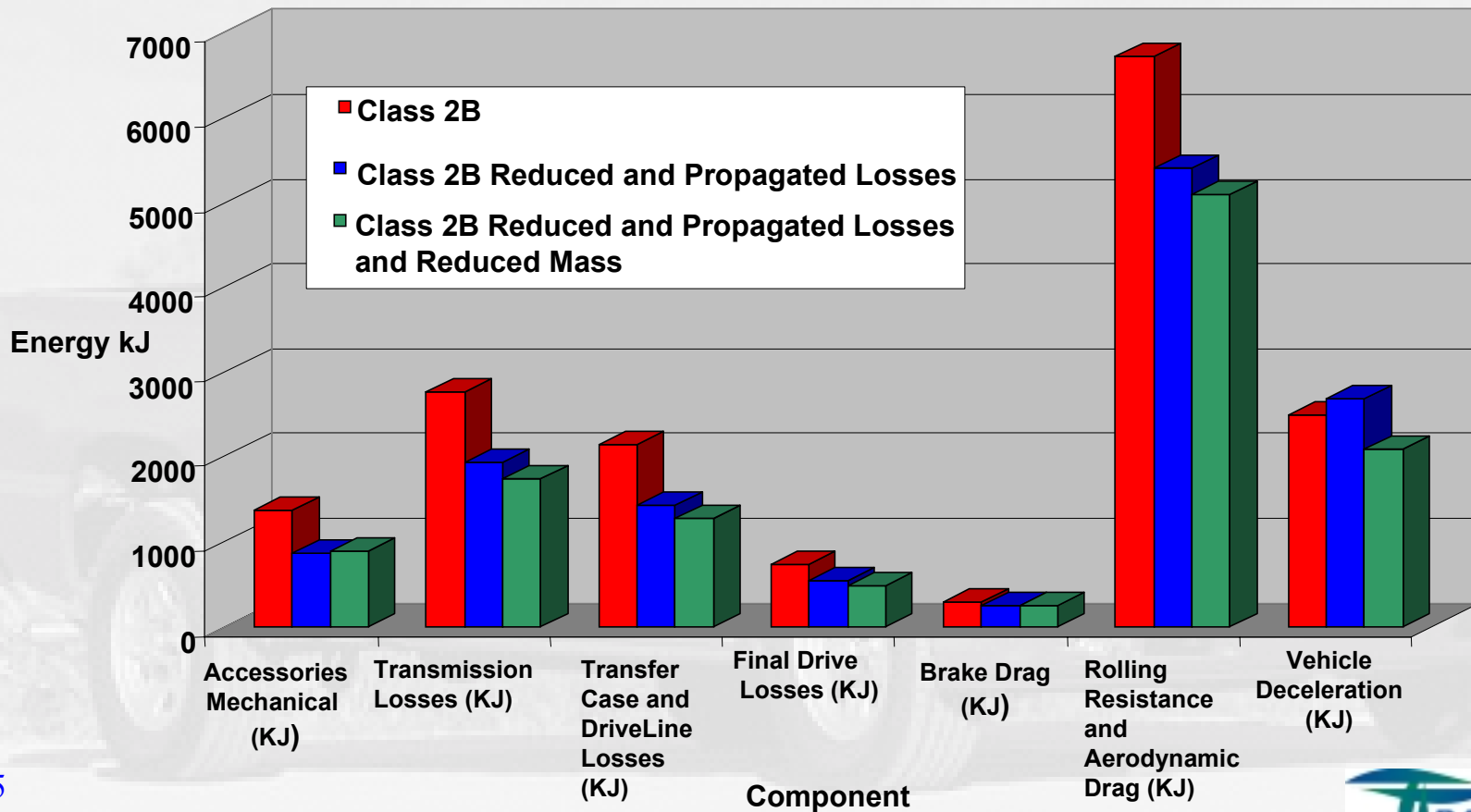
Effect of Dieselization

EPA Combined Fuel Economy | 26.7 mpg (gas equivalent)

Class 2B Reduced and Propagated Losses Compared to Baseline Class 2B (SI)

Legend:
- ■ Class 2B (SI)
- ■ Class 2B (CI) Reduced and Propagated Losses
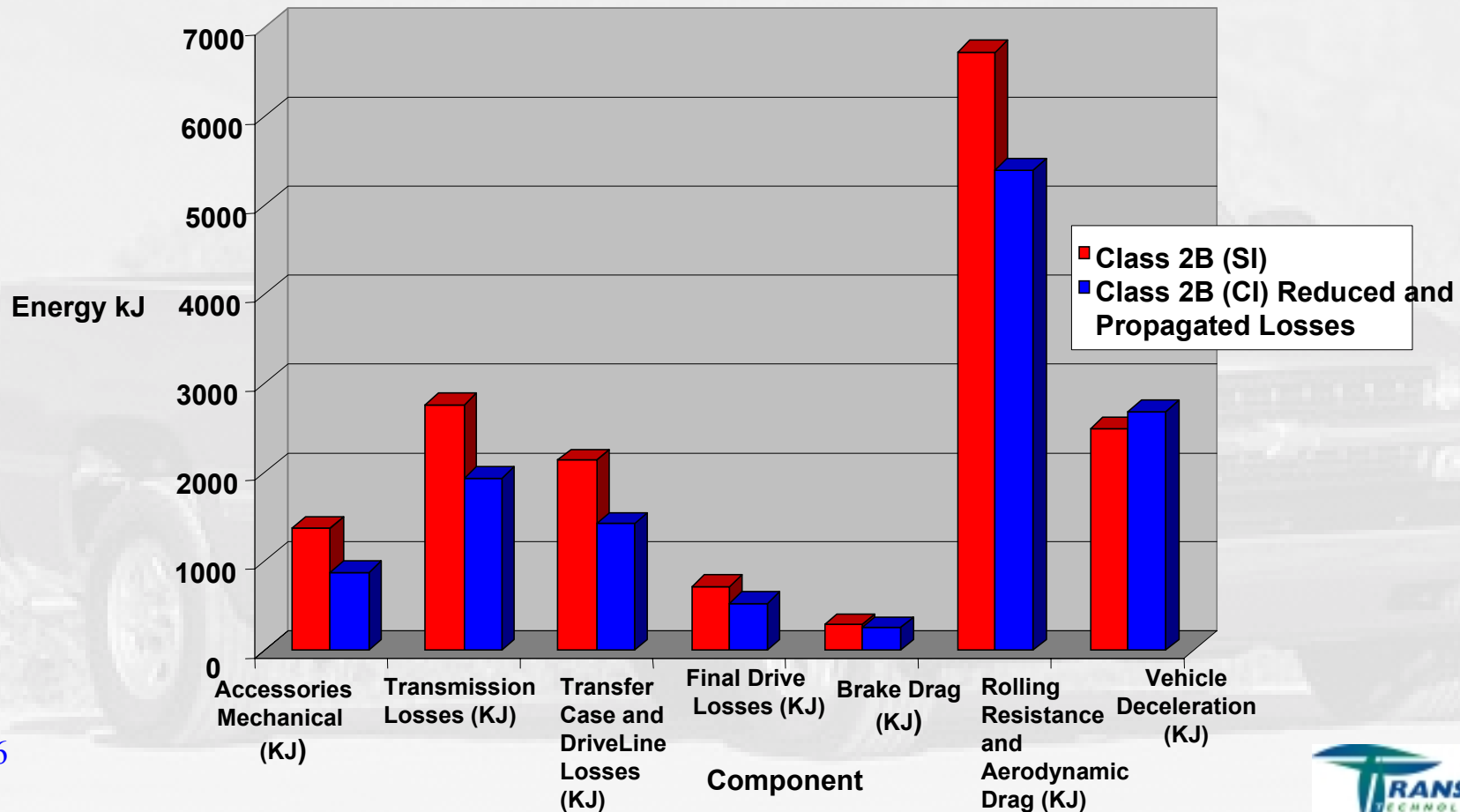
- Starter Alternator Parallel Configuration
- 6.5L CI Engine
- 144 volt, 6Amp-hr, NiMH Battery
- 16kw Permanent Magnet Motor
- Automatic Transmission
- Used 21st Century Drivetrain Losses and Vehicle Mass Reduction Targets

Control Strategy of Parallel Hybrid

➢ A Mild Hybrid Control Strategy

➢ Zero Idle

➢ Regenerative Braking

➢ Mild Assist 60 N-m of Assist

Comparison of Fuel Economy

Fuel Economy (mpg)

- 17.8 — Class 2B (SI)
- 22%
- 21.8 — Reduced Losses
- 32%
- 23.6 — Reduced Losses and Mass
- 50%
- 26.7 — CI Engine with Reduced Losses and Mass
- 74%
- 31.0 — CI Engine Mild Hybrid

Class 2B Drivetrain

19

TRANSPORTATION TECHNOLOGY R&D CENTER
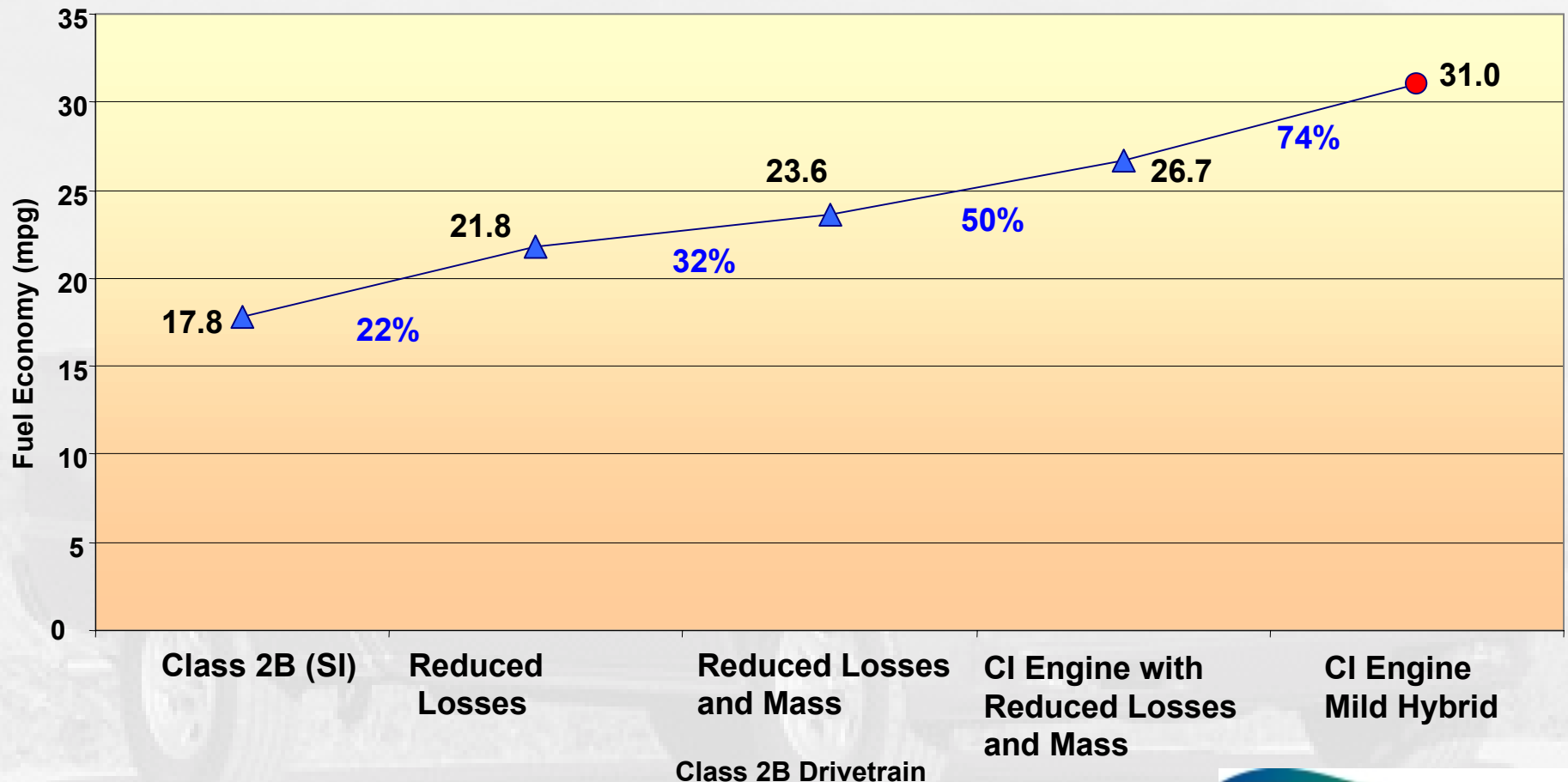
Conclusions

➢ **21ˢᵗ Century Truck targets lead to a 50% gain in fuel economy when compared to the baseline class 2B on the EPA Combined Cycle**

- A 22% gain in fuel economy is possible by reducing the losses of each drivetrain component by 20%.
- An additional 8% gain is obtained by decreasing the mass of the truck
- An additional 13% gain occurs by changing to a Diesel engine

➢ **Mild hybridization (without engine downsizing) yields an additional 16% gain in fuel economy**

➢ **Cumulative gain is 74% over the baseline**

2001 ADVISOR/PSAT User Conference

Tuesday Special Presentation

Argonne's Hybrid Electric Vehicle Technology Development Program

Aymeric Rousseau, Argonne National Laboratory

ARGONNE'S

HYBRID ELECTRIC VEHICLE TECHNOLOGY DEVELOPMENT PROGRAM

Bob Larsen
Keith Hardy
Aymeric Rousseau
Maxime Pasquier
Mike Duoba

Outline

➢ **PSAT Introduction**

➢ **Increased Transient Capabilities**

➢ **Enhanced Graphical User Interface**
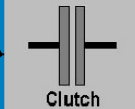
➢ **Example Of Validated HEVs**

➢ **Perspectives**
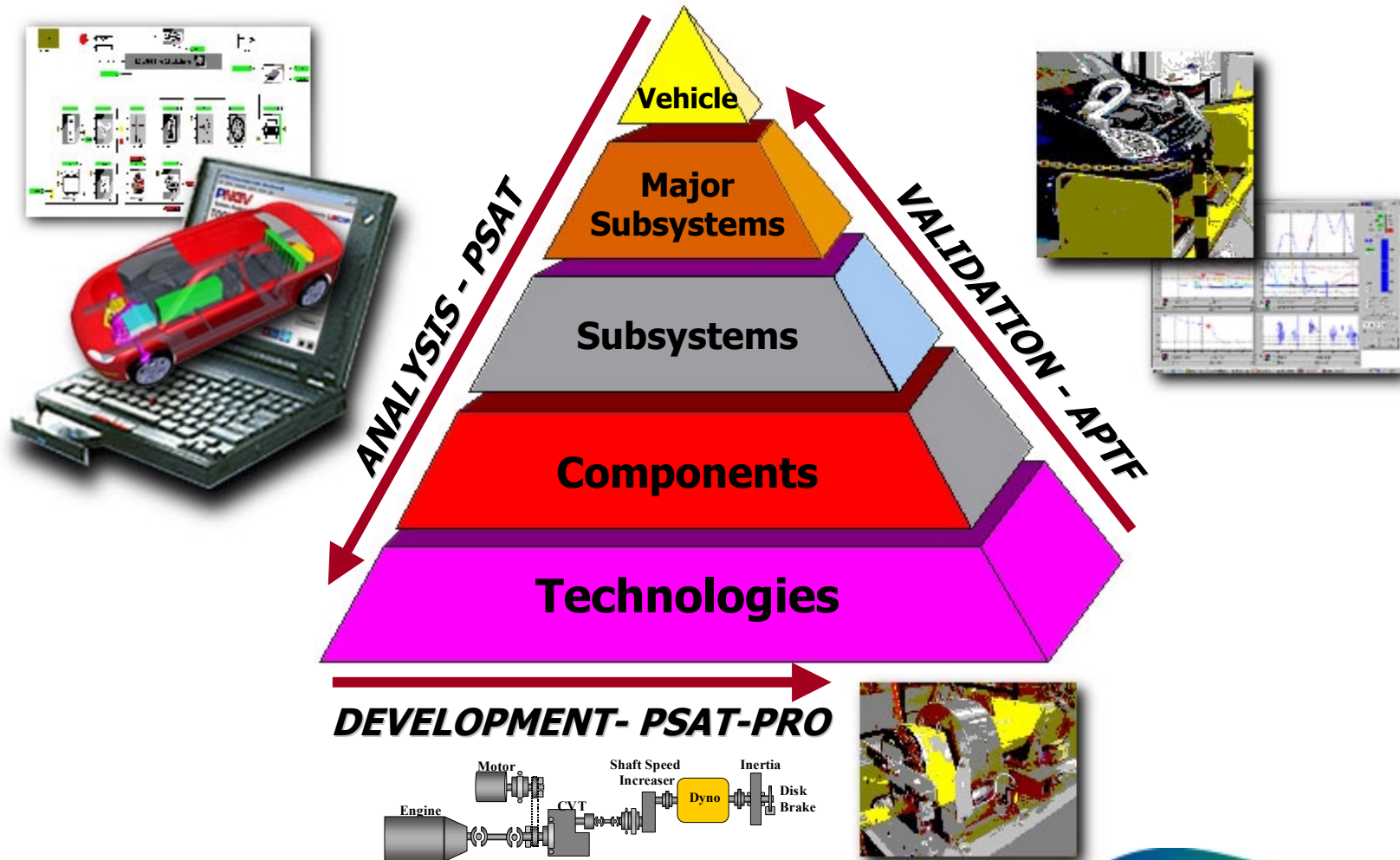
BACKGROUND

The PNGV Systems Analysis Toolkit was initiated in 1995 by USCAR (contract to TASC and SwRI).

ANL redesigned PSAT in 1999 to meet the needs of DOE's integrated analysis, hardware-in-the-loop and validation activities.

➤ **Proprietary version available to PNGV partners**

➤ **Non-proprietary version to other selected users**

➤ **Approximately 100 active users … 25 companies plus universities**

Forward modeling (driver-to-wheels) more realistically predicts system dynamics, transient component behavior and vehicle response.

Commands from a Powertrain Controller to obtain the desired vehicle speed
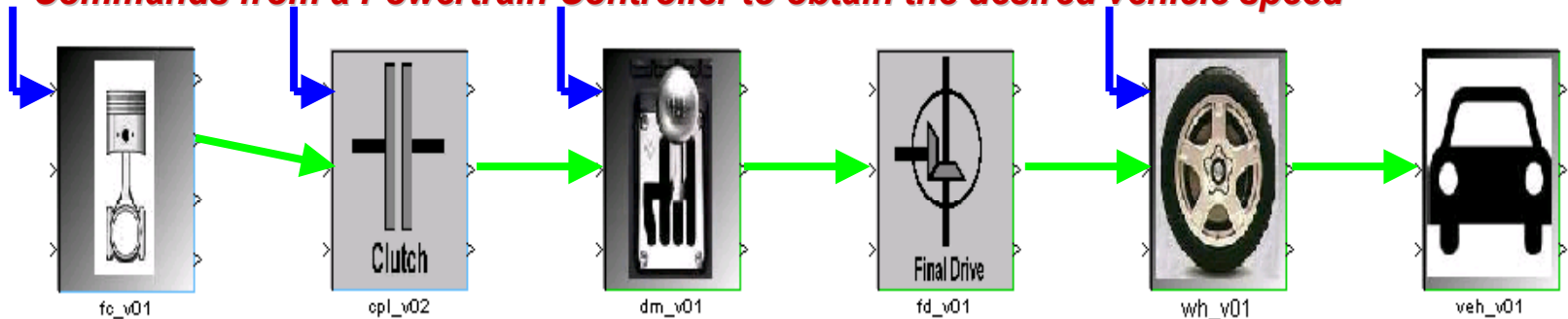
> **Consistent with industry design practice**

> **More accurately represents component dynamics (e.g. engine starting and warm-up, shifting, clutch engagement ...)**

> **Allows for advanced (e.g. physiological) engine models**

> **Allows for the development of control strategies that can be utilized in hardware-in-the-loop or vehicle testing**

> **Small time steps enhance accuracy**

5

PSAT is Flexible and Reusable

➢ **Drivetrains constructed from user choices**

➢ **Numerous configurations can be explored(>150: conventional, parallel, series, power split...)**

➢ **Several strategies can be compared within the same model using switches**

➢ **Drivetrain controllers composed of three blocks (Constraints, Strategy, Transients)**

➢ **Model format is generic (3 inputs / 3 outputs)**

➢ **Multiple uses of same model possible**

➢ **Software is highly parameterized**

PSAT is User-Friendly

➢ **Easy integration** **of initialization files, component models or control strategies through its Graphical User Interface**

➢ **Easy comparison** **of different levels of model sophistication and control strategies**

➢ **Post simulation analysis is enhanced through use of a** **voltage bus** **for more realistic transient behavior**

PSAT has been designed to take transients into account and handle different levels of modeling detail ... allowing the user to match the level of sophistication with the application.

PSAT Structure Flows Intuitively
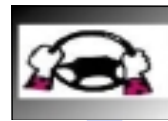
Accelerator/Brake pedal
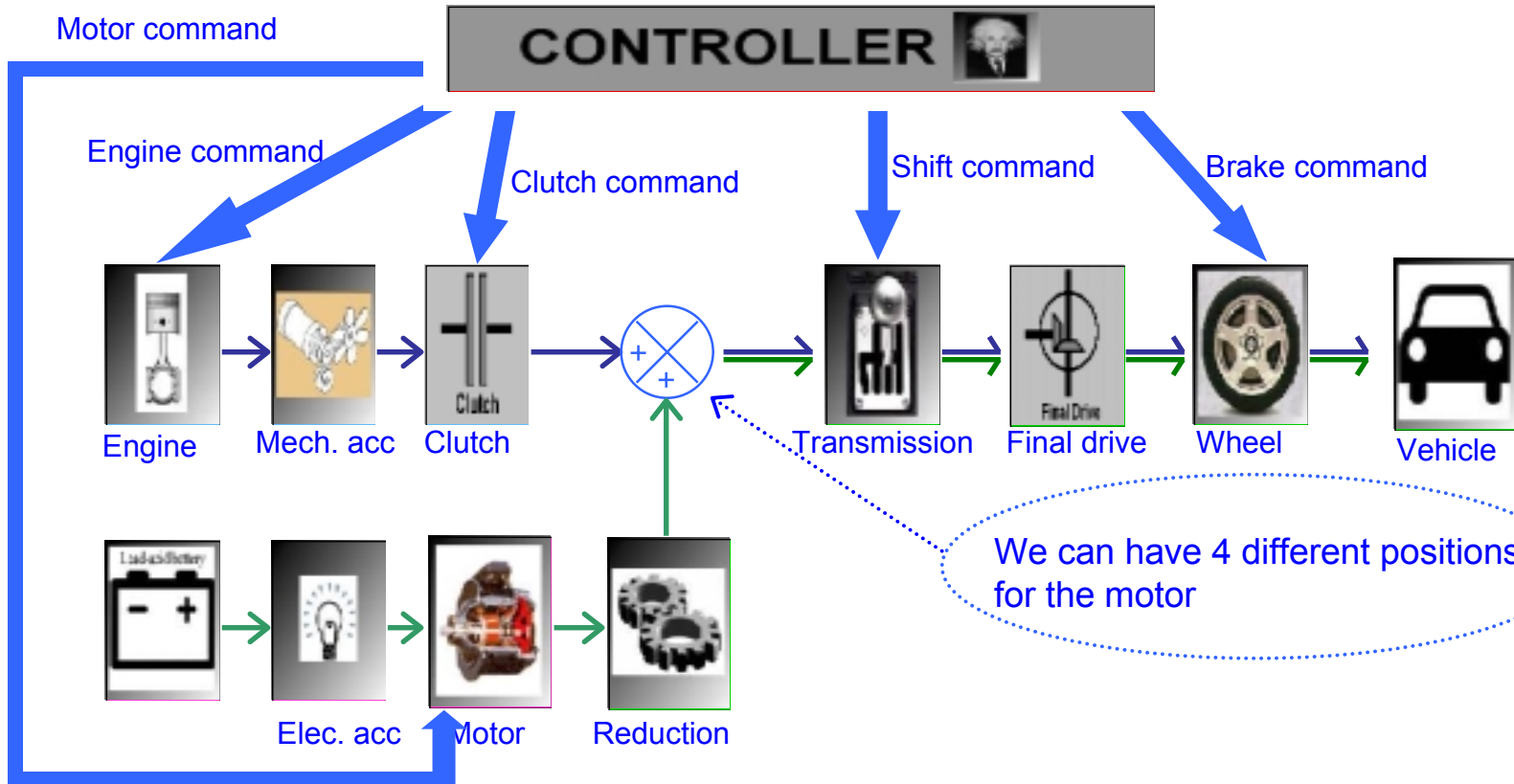
Motor command

Engine command

Clutch command

Shift command

Brake command

Engine   Mech. acc   Clutch

Transmission   Final drive   Wheel   Vehicle

Elec. acc   Motor   Reduction

We can have 4 different positions for the motor
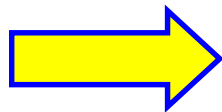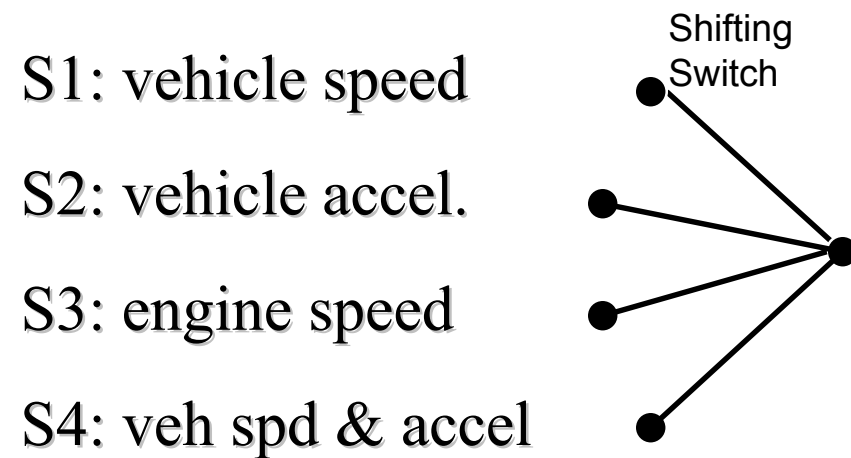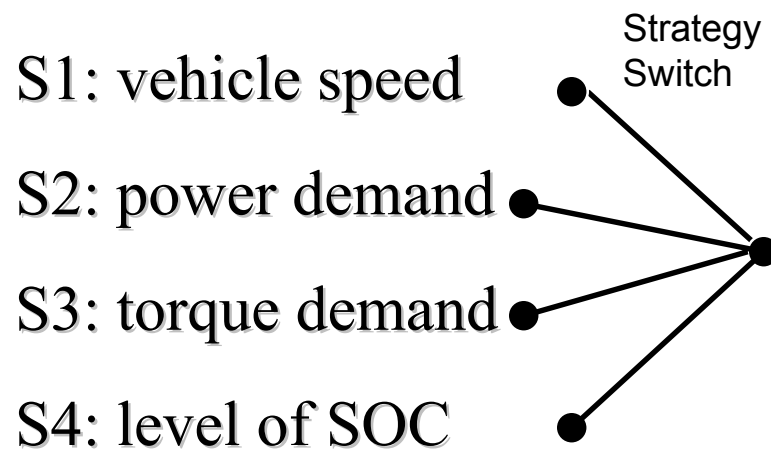
Outline

➢ **PSAT Introduction**

➢ **Increased Transient Capabilities**

➢ **Enhanced Graphical User Interface**

➢ **Example Of Validated HEVs**

➢ **Perspectives**

Transient Fuel Cell Model Approach

Develop engineering models of FC systems and components using the GCtool architecture.

➢**GCtool is design-oriented ... models are too slow (complex) for transient driving cycles**

➢**Details may not be available for building mechanistic models**

➢**Flexible to arrange component configuration**

➢**Some existing models can be adapted**

Translate to MATLAB executable from GCtool.

Executable becomes part of the PSAT library.

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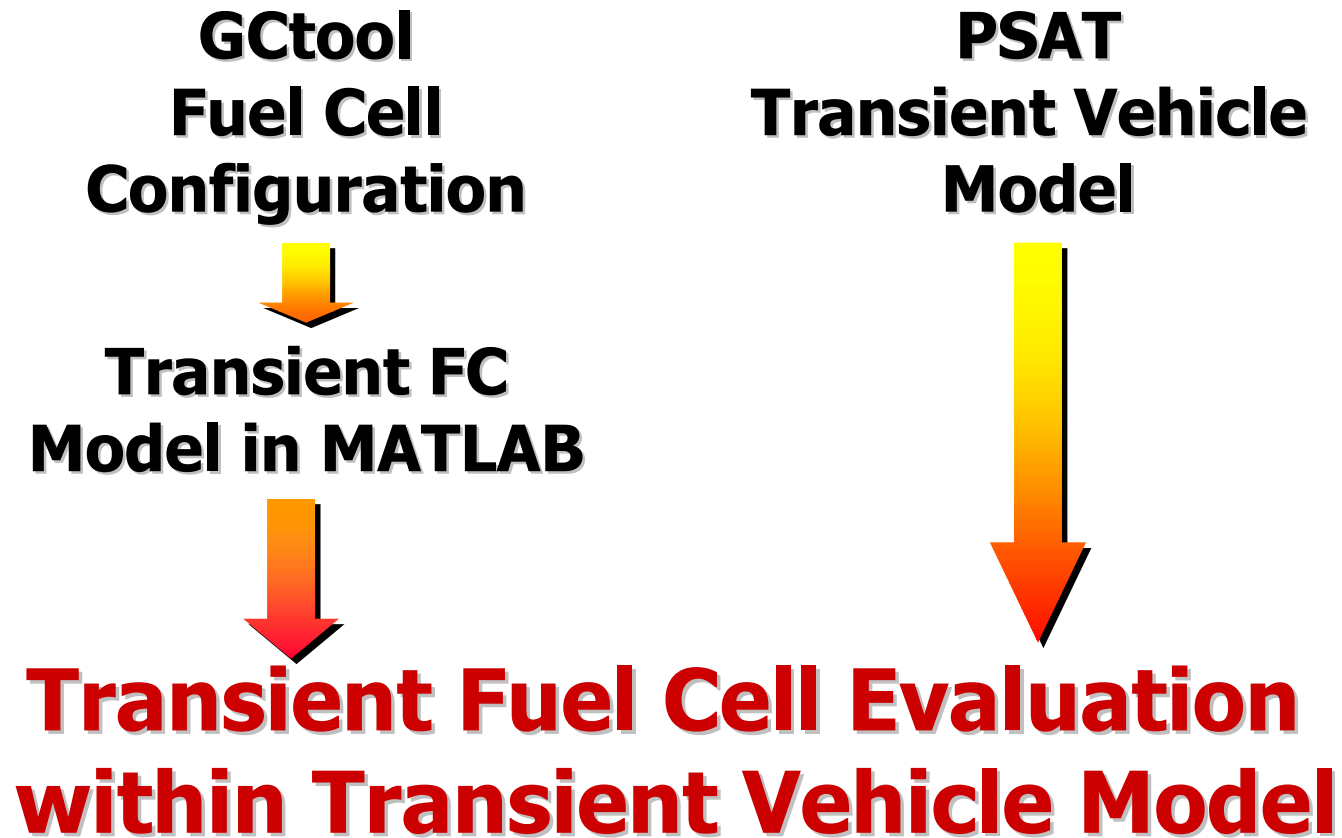
Neural Network Engine Model

➢ **Use APTF transient data to generate a NN model of the Japan Prius**

➢ **Develop unique capabilities and methodology for the selection of**

   ➢**the I/O**

   ➢**the type of NN**

   ➢**the number of layers**

➢ **Model produced with 1Hz data shown compelling results**

13

Clutch Engagement / Disengagement

Parameters (in/out) are related to the clutch

Example of gear shifting in PSAT
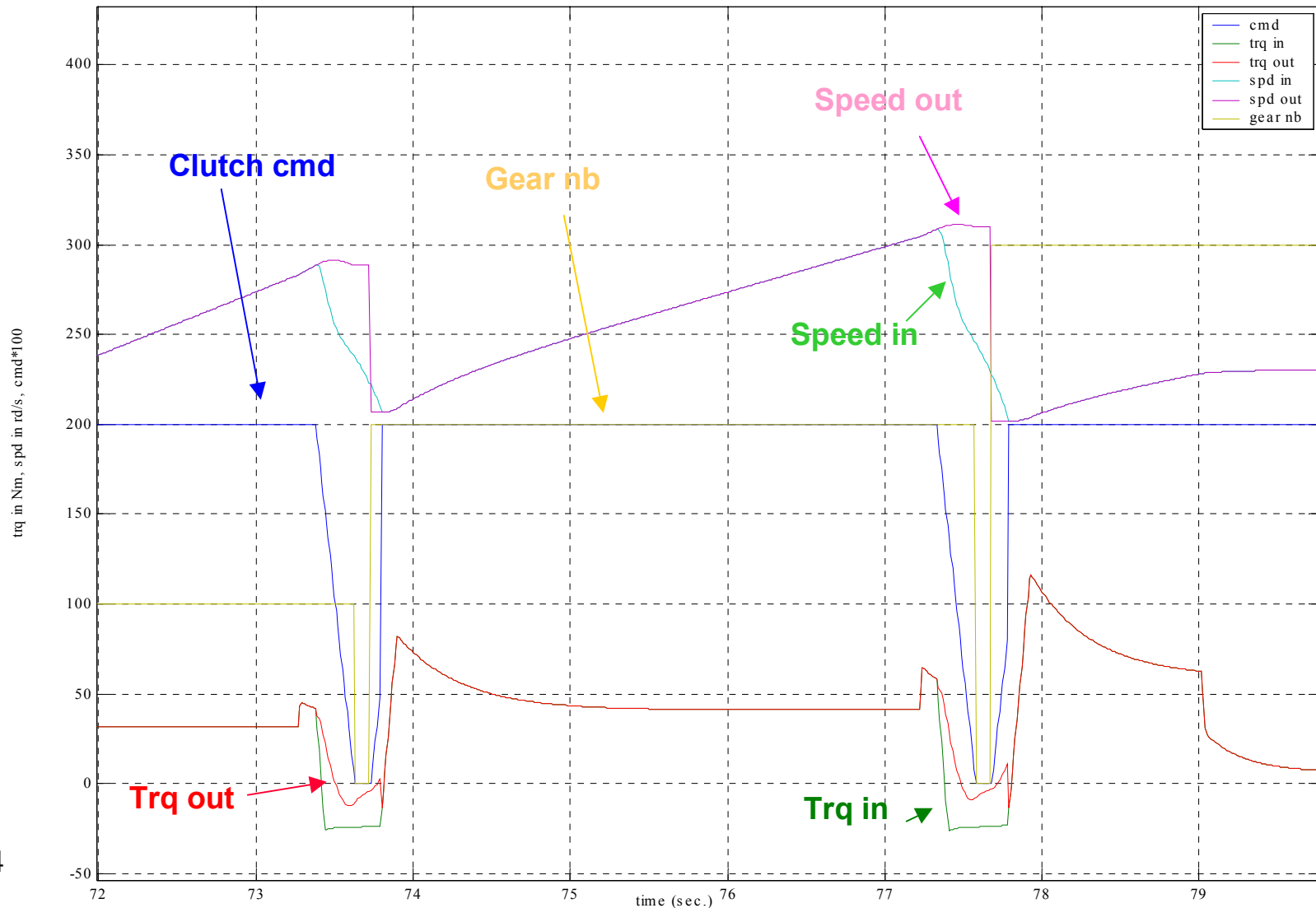
Outline

➢ **PSAT Introduction**

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➢ **Perspectives**

PSAT Graphical User Interface

- ➢ **PSAT GUI is based upon 4 main windows:**

  - ➢ **<u>Initialization</u> – Choose the configuration and the components**

  - ➢ **<u>Test choice</u> – Choose the type of test(s) to be realized**

  - ➢ **<u>Results</u> – Access to the final results and plots**

  - ➢ **<u>Post-processing</u> – Display the energy, power… of the different components**

- ➢ **Several other windows are then used to:**

  - ➢ **Integrate new data, models or control strategies**

  - ➢ **List the parameters of each model and control strategy**

  - ➢ **Run multi-cycles or create a trip**

  - ➢ **Save the simulation(s)**

Adding Control Strategies Is Easy

APTF Test Data

PSAT Simulation

Strategy Understanding Validation

Control Strategy Understanding, Model Validation

Importing Test Data Into PSAT is Easy

Step7
Plot parameters

Step6
Save the template

Step1
Load Data
From TXT file

Step3
Rename each Data using PSAT Nomenclature

Step2
Delete Unwanted Data
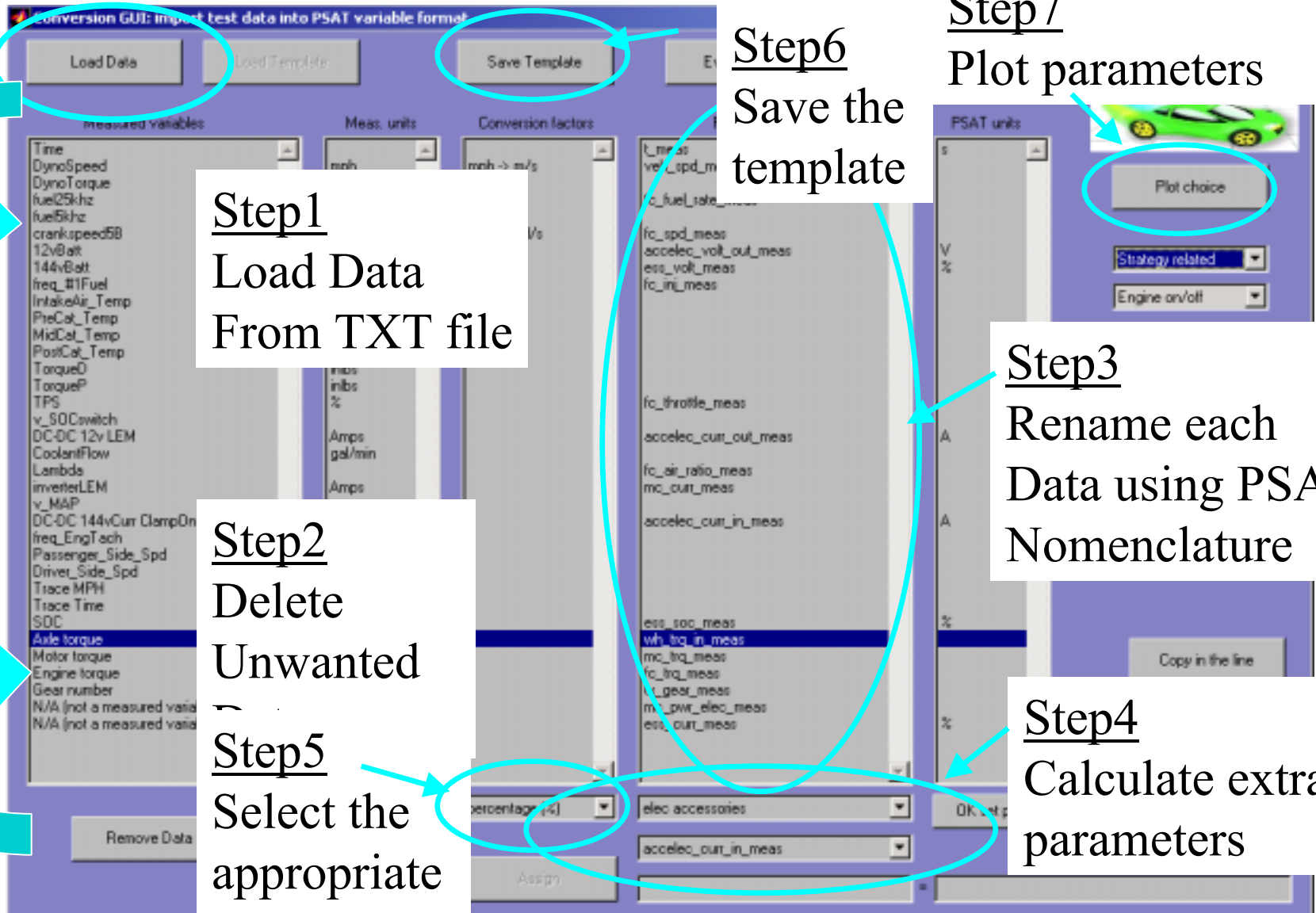
Step5
Select the appropriate units

Step4
Calculate extra parameters

20

Generic, Flexible Animation Window

Effort/Power Representation

Vehicle Status

Possibility to plot all the data and single points

Play the simulation Step by step

Sim and Meas data on the same plots

X and Y Axis easy to select
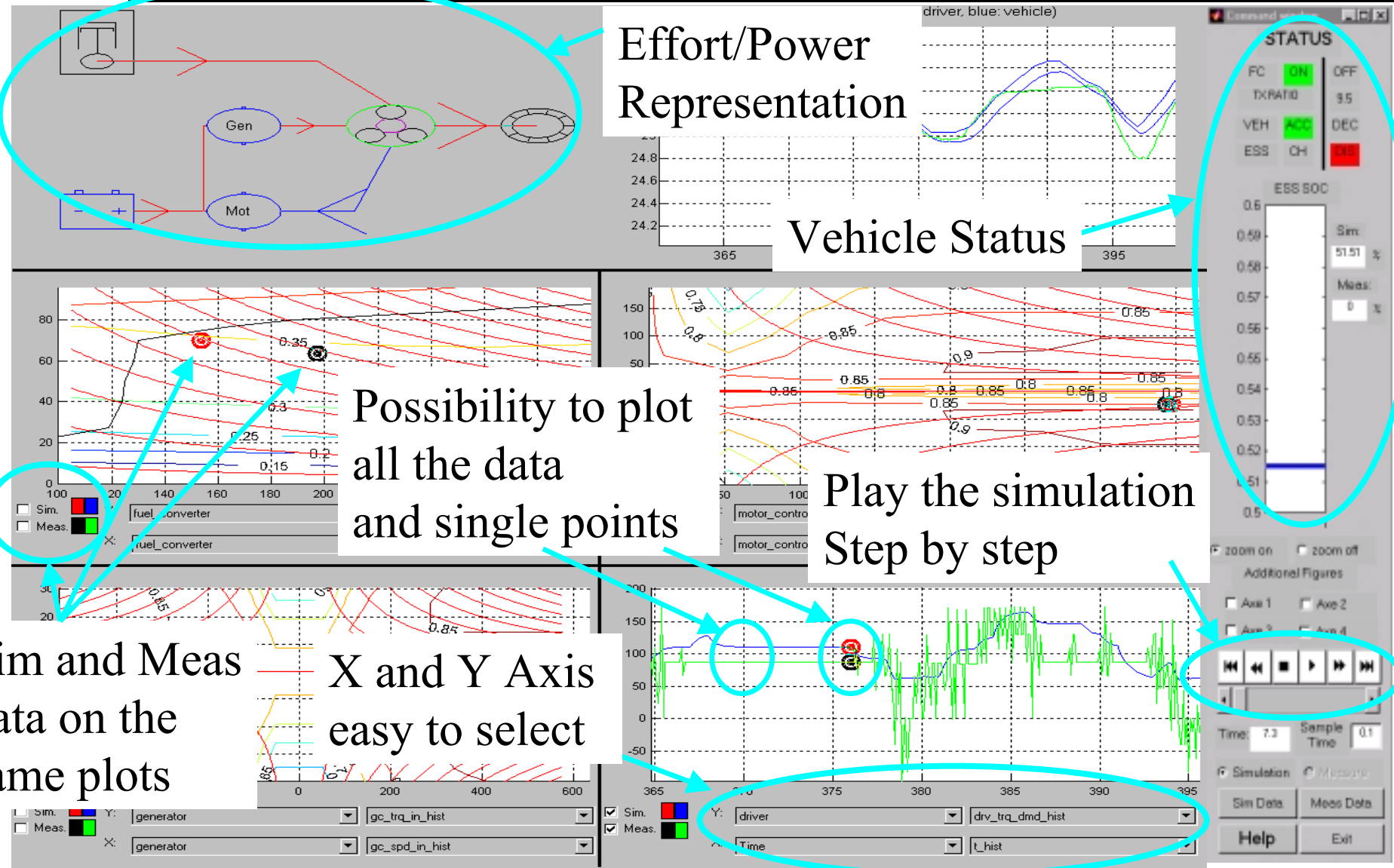
Animation Window Main Characteristics

➤ Facilitate the understanding of the control strategy using only simulated or measured data

➤ Comparison of simulated and measured data for validation

➤ Provides the states of the system and the effort/flow information of each component

➤ X and Y plot axis can be naturally changed

➤ Allow the user to pause and go back and forth

➤ Possibility to change the speed of the animation

➤ Works for any simulation algorithm (fixed and variable steps) and any PSAT configuration

Outline

➢ **PSAT Introduction**

➢ **Increased Transient Capabilities**

➢ **Enhanced Graphical User Interface**
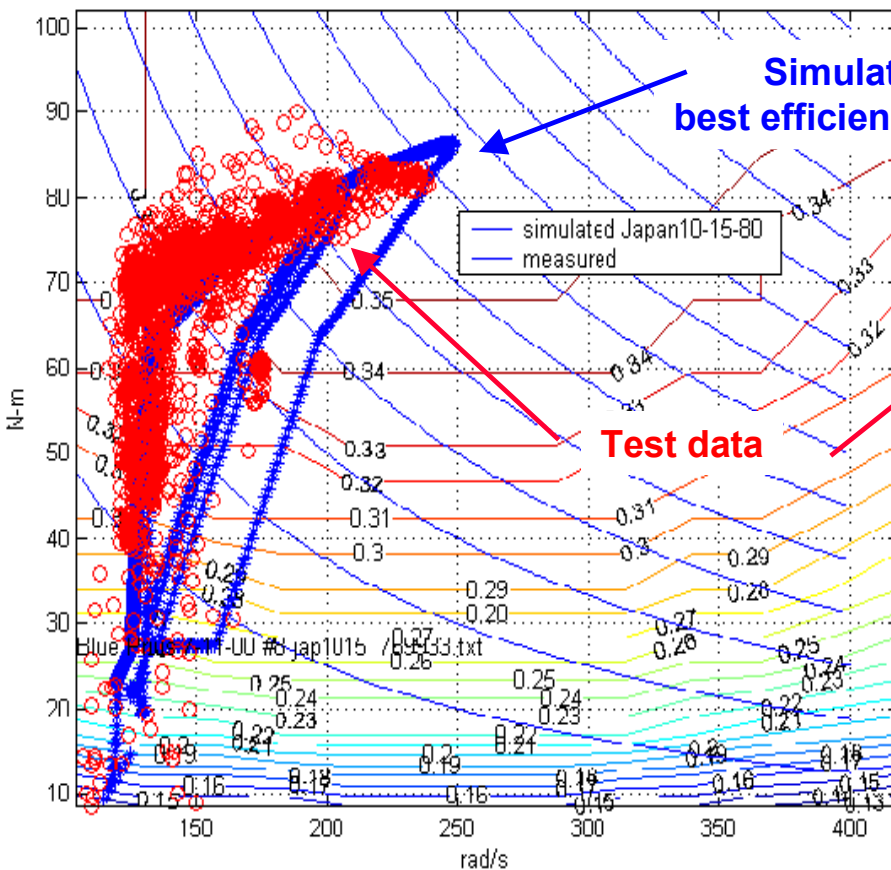
➢ **Example Of Validated HEVs**

➢ **Perspectives**

Engine torque vs. Engine Speed
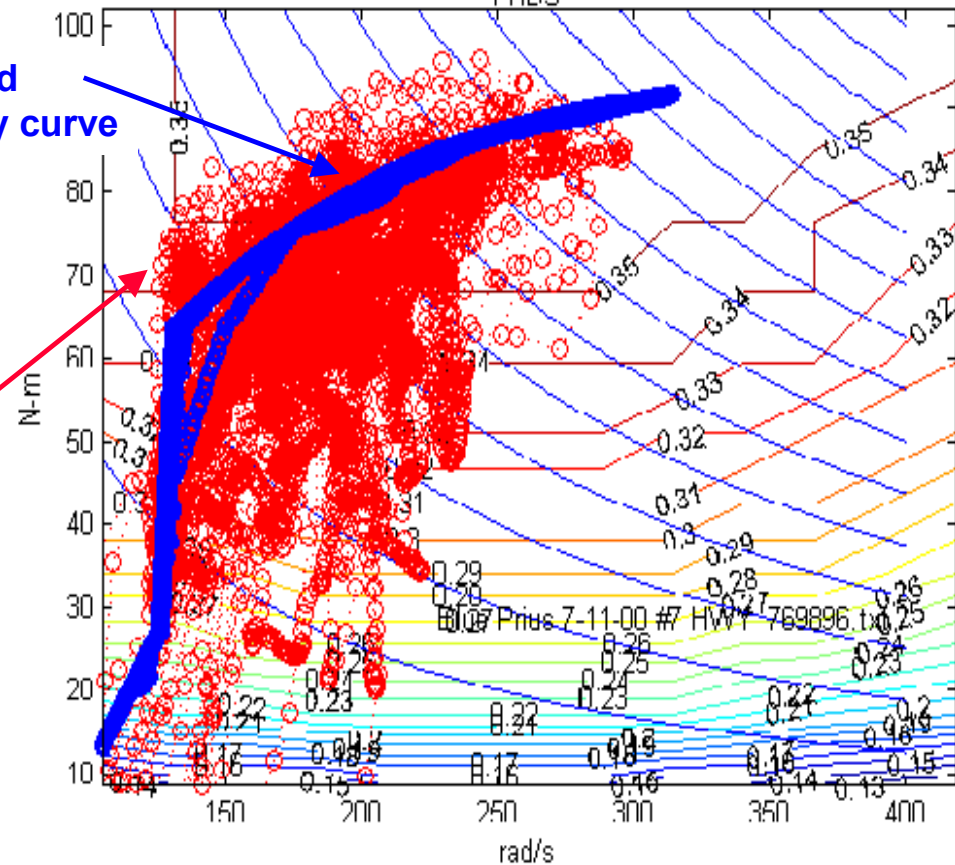
Japan 10-15

FHDS
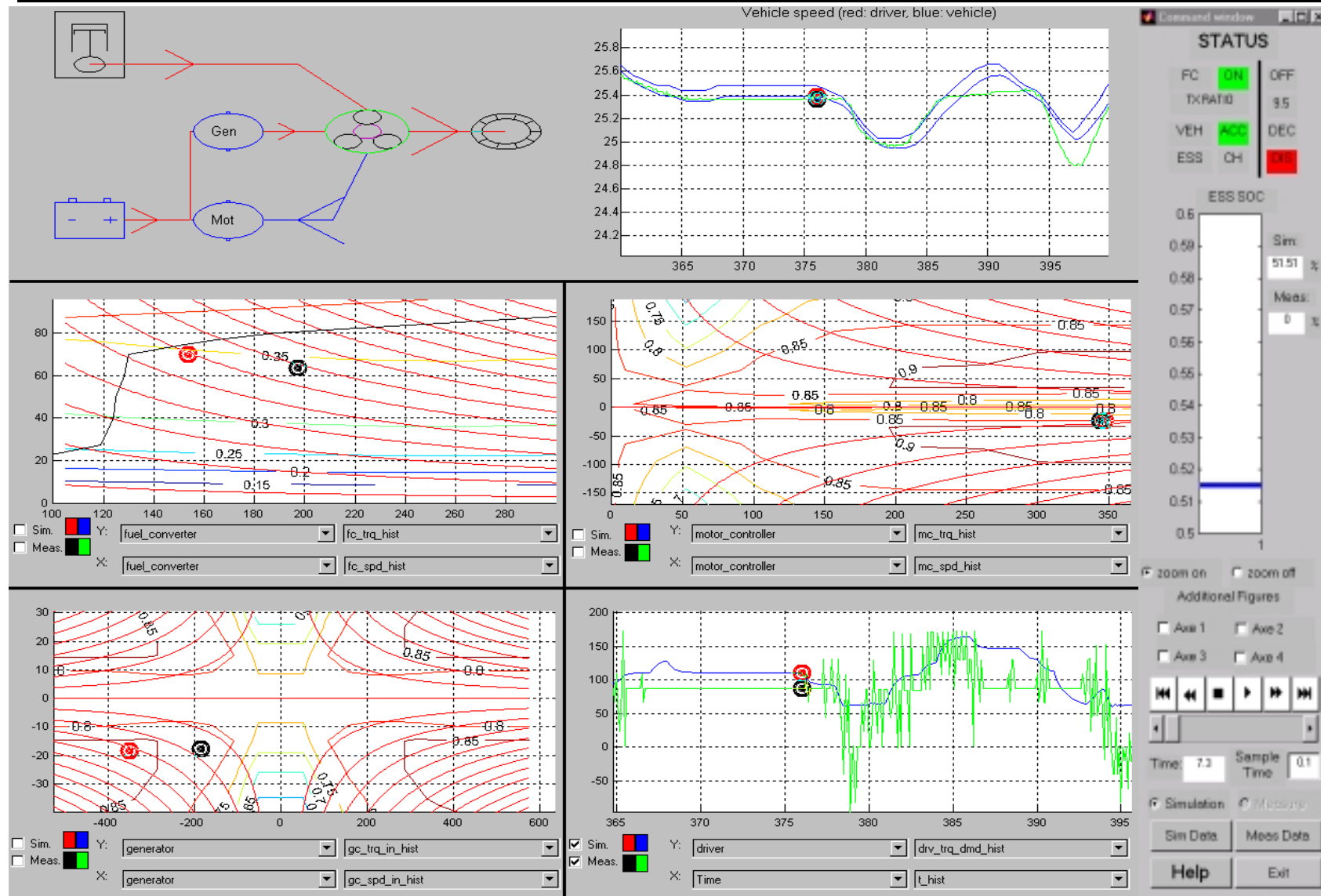
PSAT Prius FE Validation Is Within 5%

Cycle	Cons test mpg	Cons simul mpg	Diff in %	SOC init	SOCf test	SOCf simul	Diff in %
Japan 10-15	44.9	45.1	0.4	0.600	0.580	0.583	0.5
Japan 10-15	48.8	50.7	3.9	0.610	0.575	0.561	2.3
EUDC	44.0	43.8	0.4	0.610	0.605	0.593	2.0
FHDS	48.2	46.7	3.2	0.550	0.571	0.573	0.3

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Component Behavior Is Validated

Engine Speed
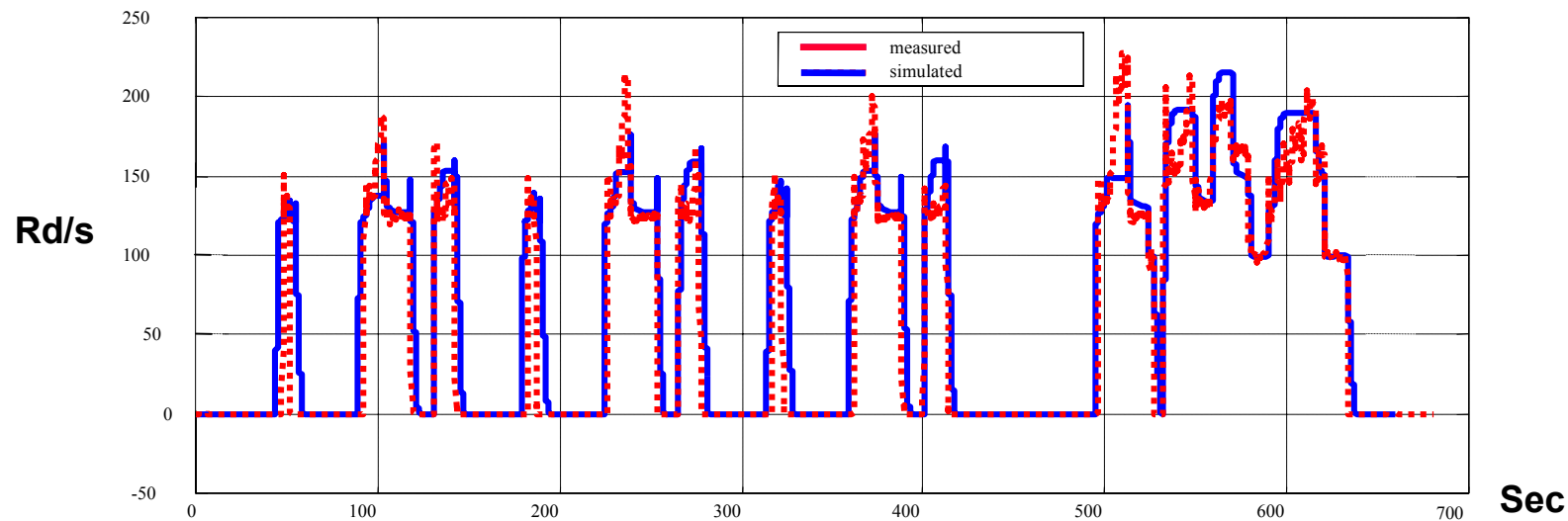
Engine Torque
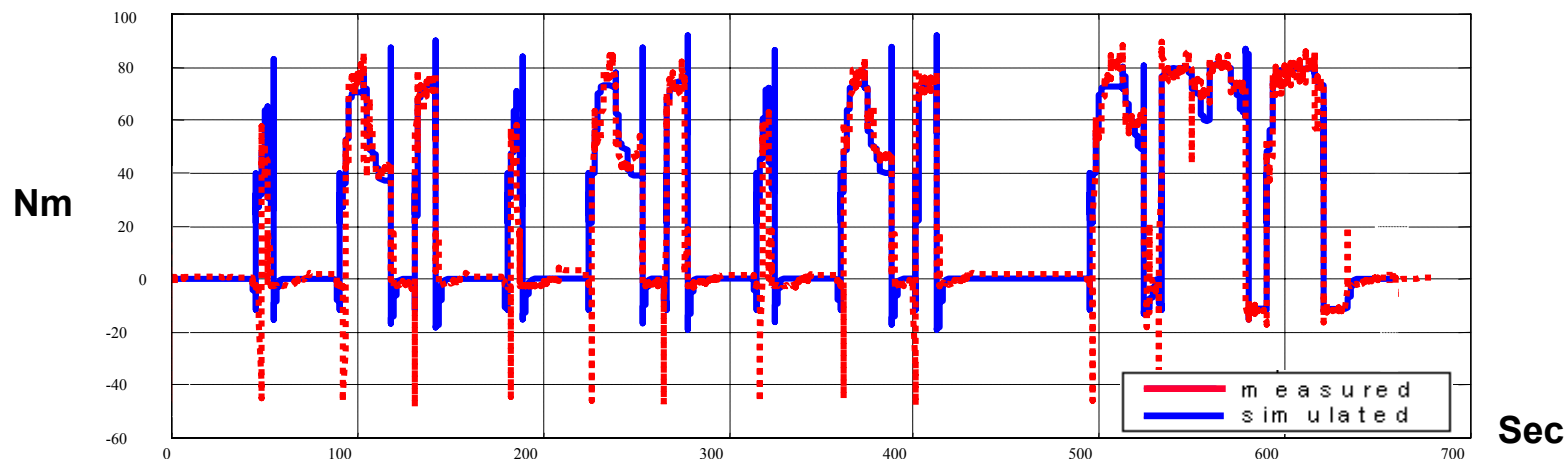
Honda Insight Testing at APTF

Insight on chassis dynamometer

Data collection: vehicle speed, engine speed, battery voltage, axle torques …

However, engine torque not directly measured

Post processing: engine torque calculation

Post-processed results
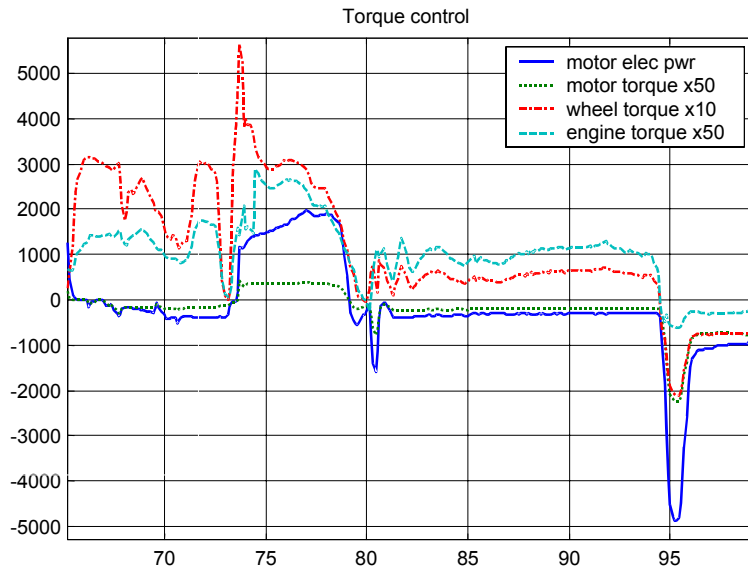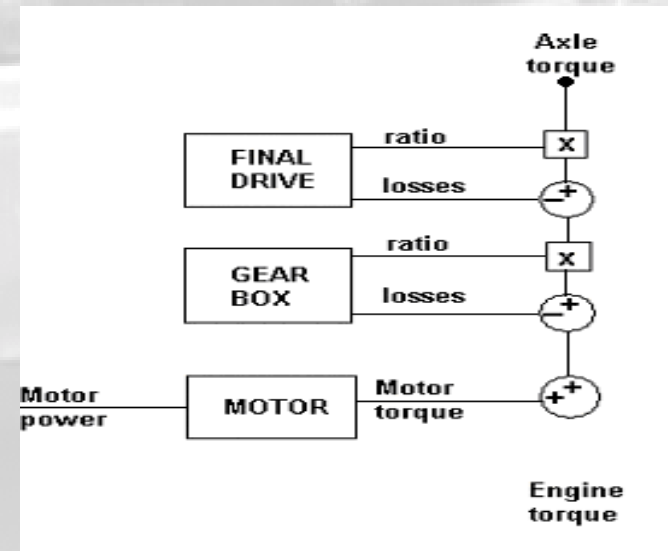
Honda Insight Cycle Validation

Japan 10-15
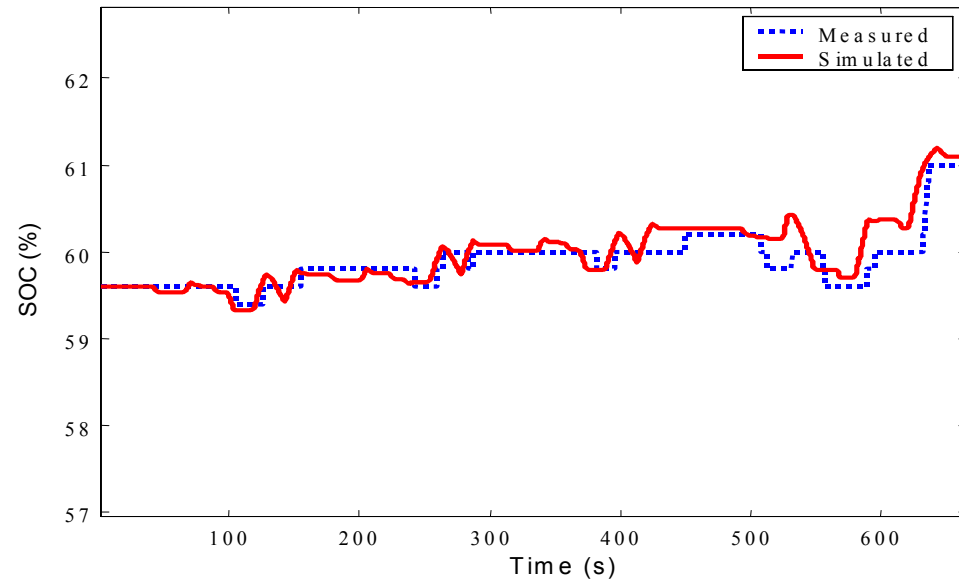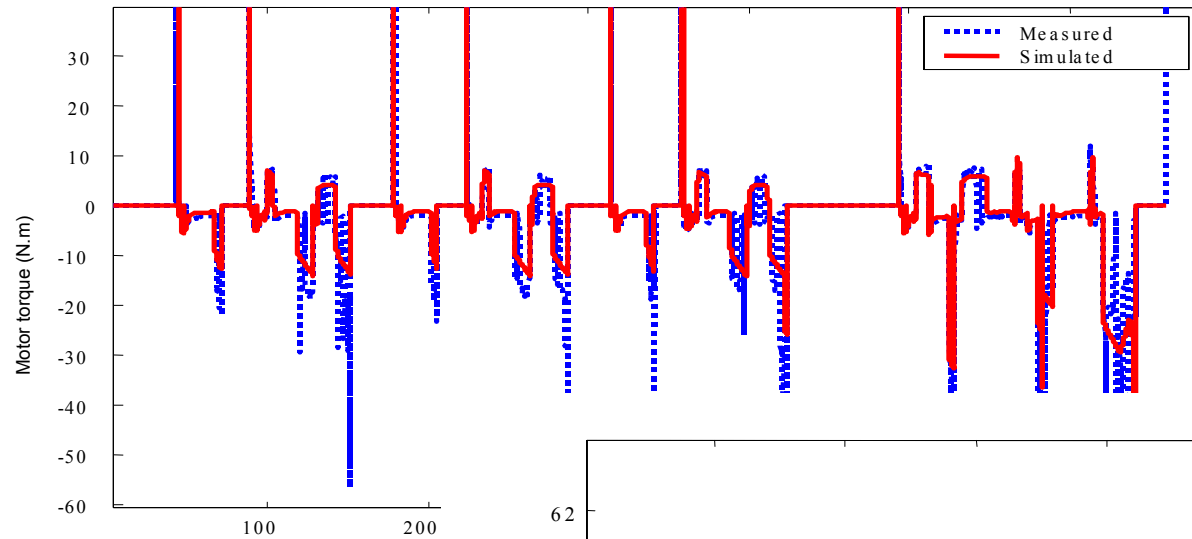
PSAT Insight FE Validation Is Within 5%

Cycle	Cons test mpg	Cons simul mpg	Diff in %	SOC init	SOCf test	SOCf simul	Diff in %
Japan 10-15	57.9	58.8	1.5	0.596	0.610	0.611	0.4
NEDC	60.6	60.2	0.6	0.600	0.602	0.583	3.6
FHDS	74.2	75.3	1.4	0.590	0.588	0.589	0.2
FUDS	58.3	57.8	0.8	0.728	0.706	0.720	2.0

- ➢ **PSAT, as a forward-looking model, is used by DOE for detailed analysis including transients and realistic control strategies**

- ➢ **PSAT has been validated over the past years for several vehicle sizes and configurations**

- ➢ **PSAT is actually being copyrighted and will be soon available to the public**

Vehicle Systems Optimization and Linking of Tools Using Co-Simulation

Application of Optimization Tools to Vehicle Systems Analysis

Min Sway-Tin and Jinbiao Li, DaimlerChrysler Corporation;
Charles Yuan, Engineous Software;
Tony Markel, National Renewable Energy Laboratory

Design and Performance of Derivative-Free Optimization Algorithms Used with Hybrid Electric Vehicle Simulations

John Whitehead, University of Michigan

Co-Simulation of Electrical and Propulsion Systems Using ADVISOR and Saber

John Macbain and Joseph Conover, Delphi Automotive Systems;
Valerie Johnson, National Renewable Energy Laboratory

Engine: 4.7L V-8

EATX 4 Spd. w/Lock Up T/C

50 Kw Motor / 20 Kw Generator

2 Kw-Hr Battery Pack

4 WD Transfer Case

Electronic Control Module

CONTRACTOR SPECIAL
Hybrid Powertrain / 20 Kw Generator Feature
Base Vehicle: 2000 MY Dodge Quad
Cab Ram 2500 w/ATX
and 4WD
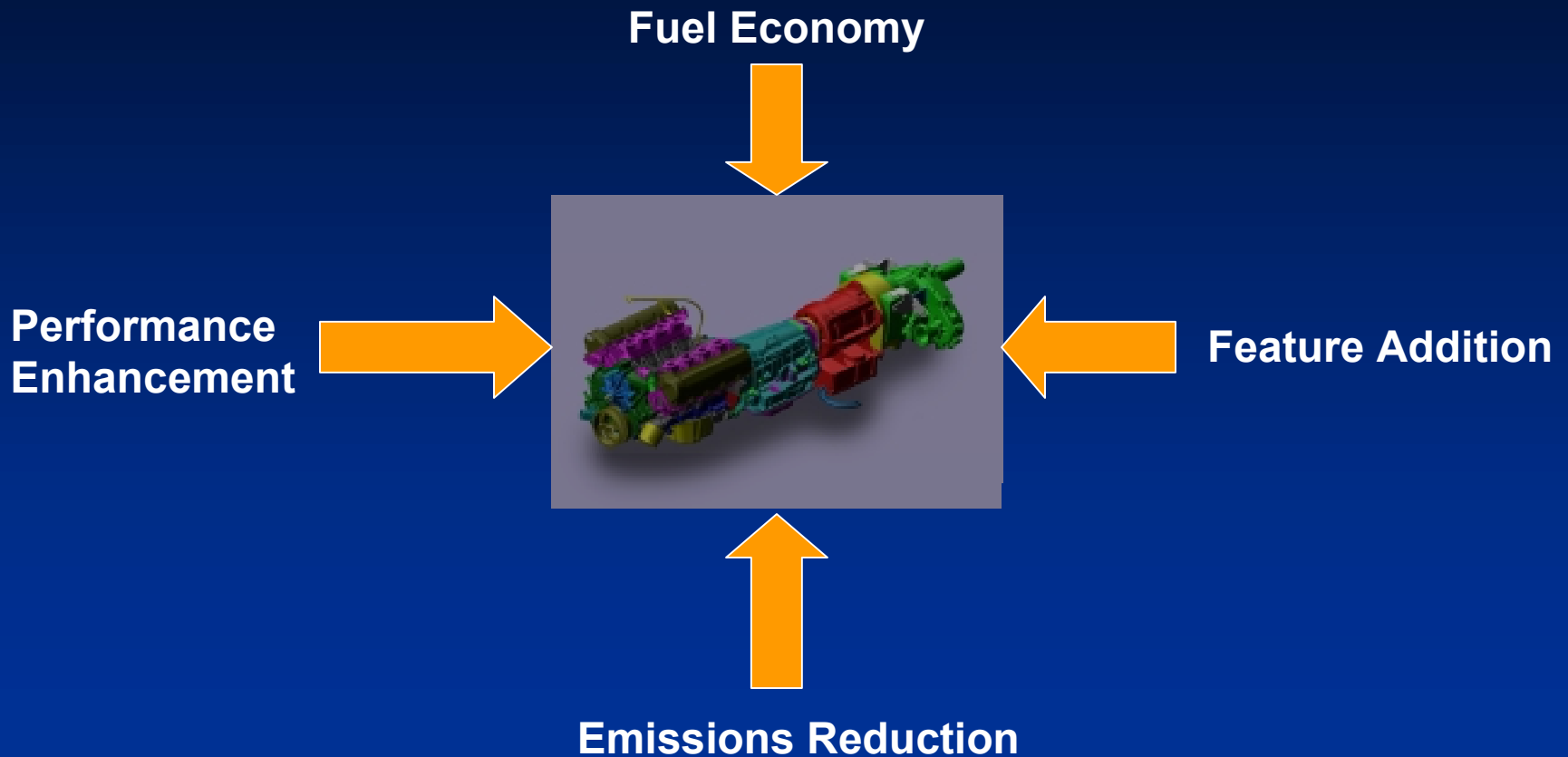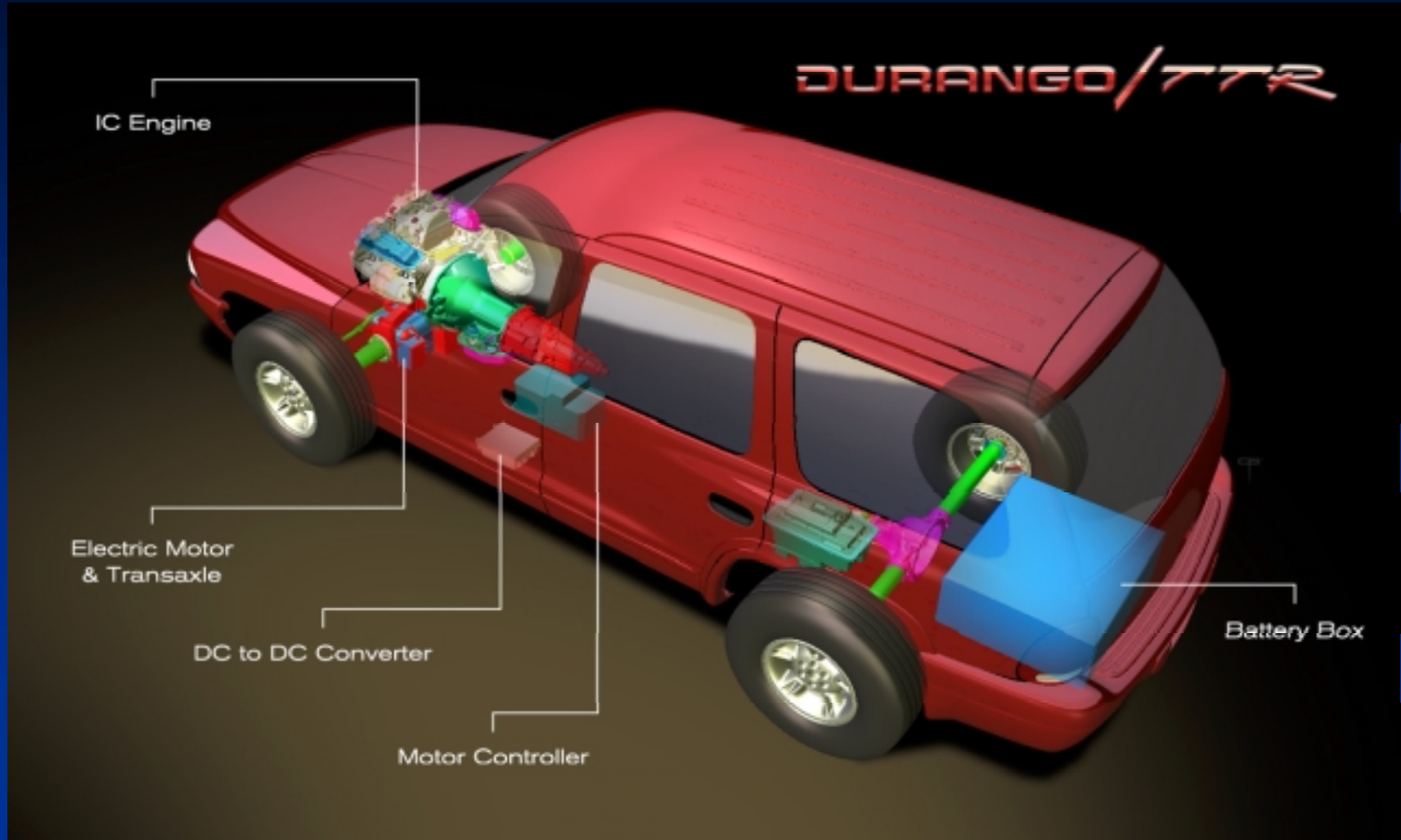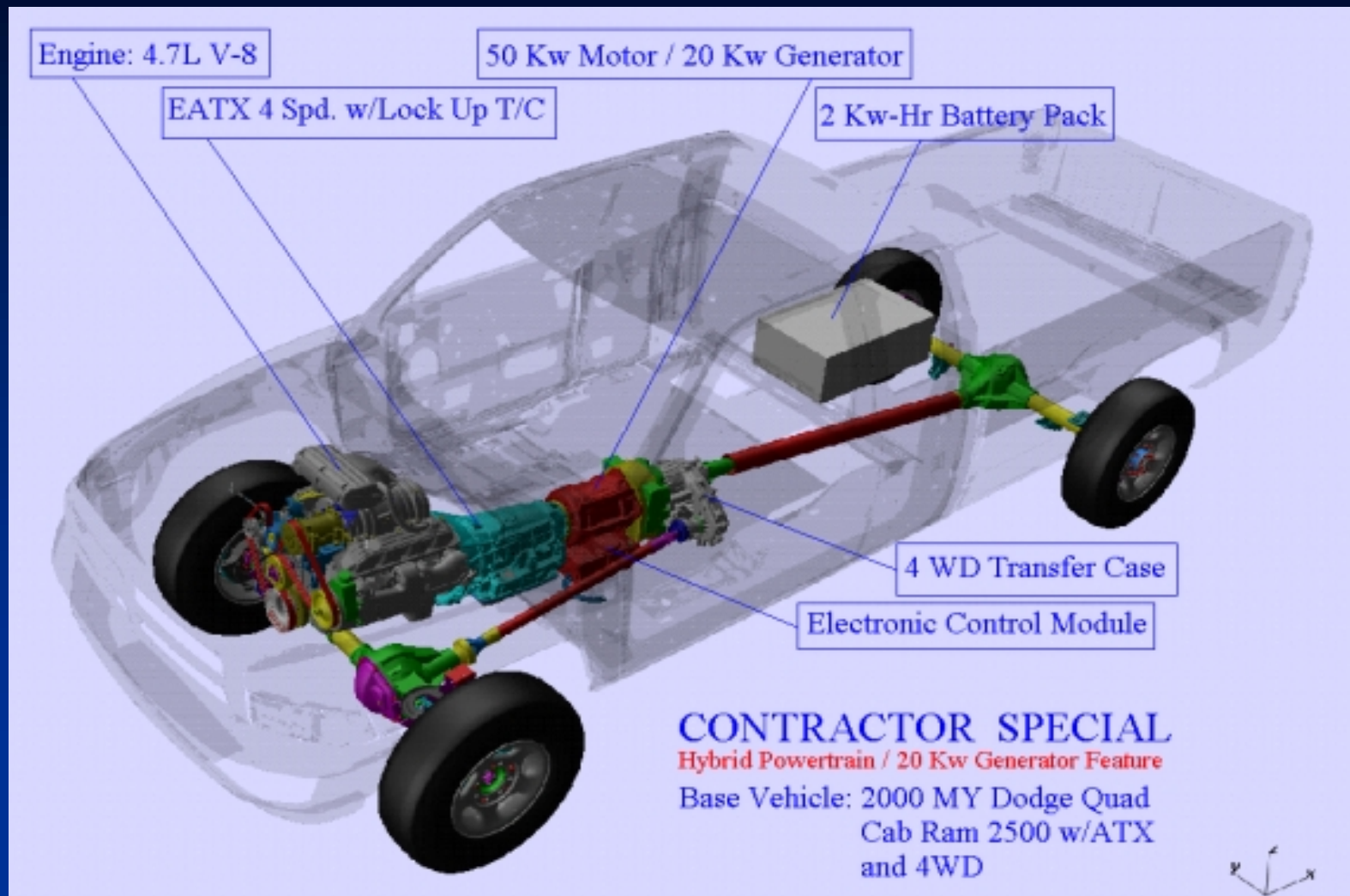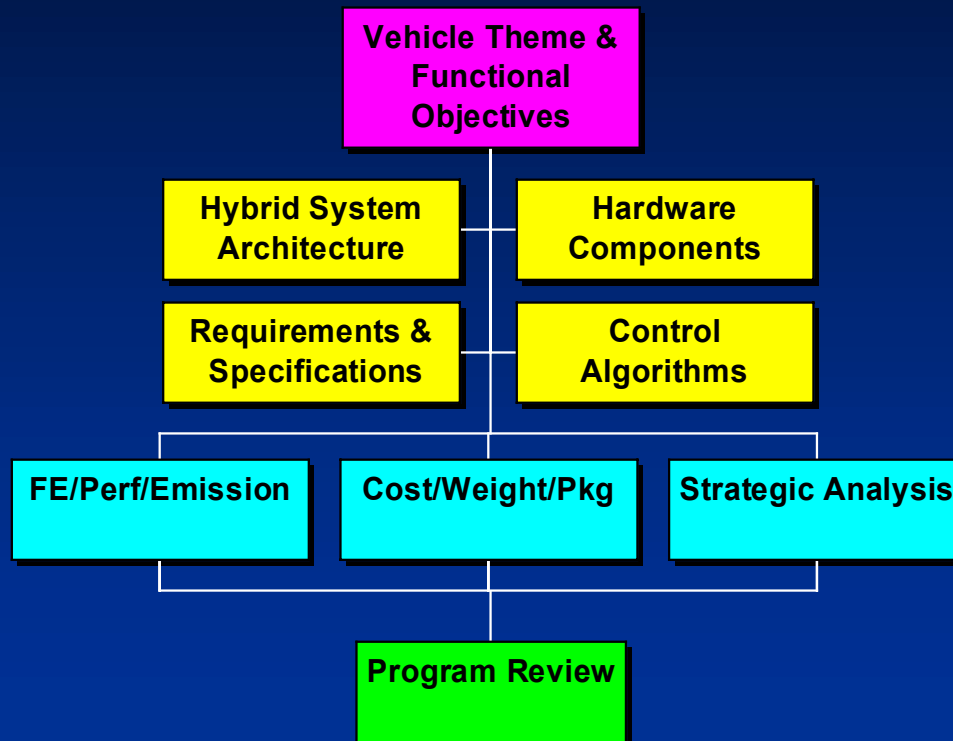
HEV Architectures

SERIES HYBRID
- Electric Generation / Charging

PARALLEL HYBRID (Mild to Full Hybrid)
- Belt-Drive Starter-Alternator
- 42V Integrated Starter-Alternator-Damper (ISAD)
- Fully Integrated Starter Generator (ISG)
- Through-The-Road Hybrid (TTR)
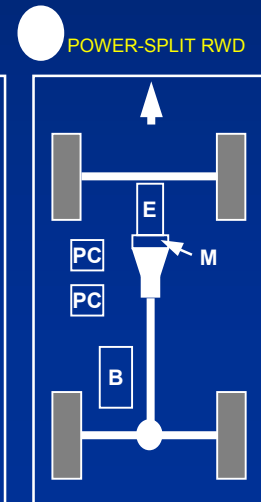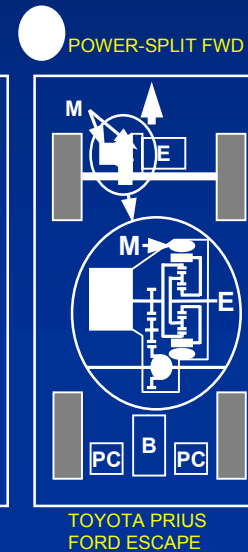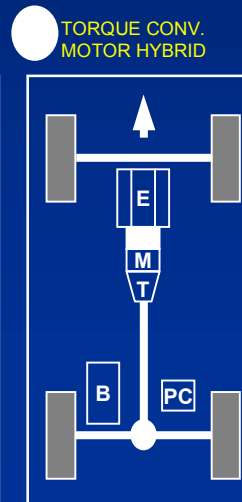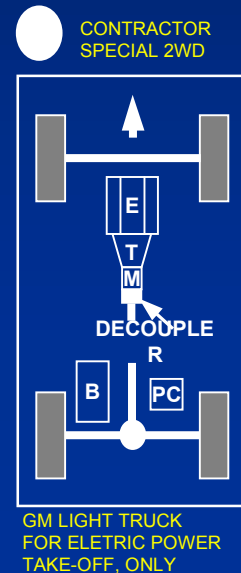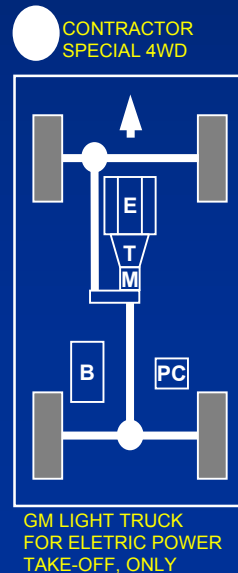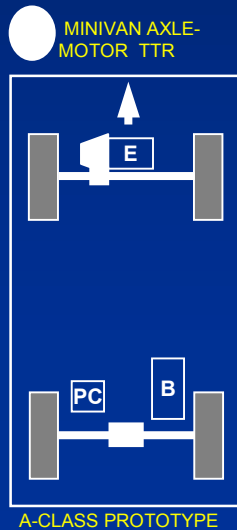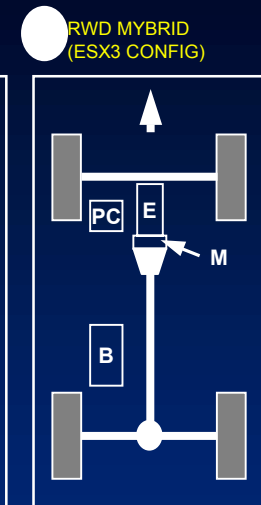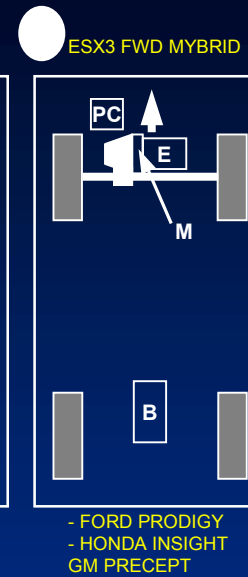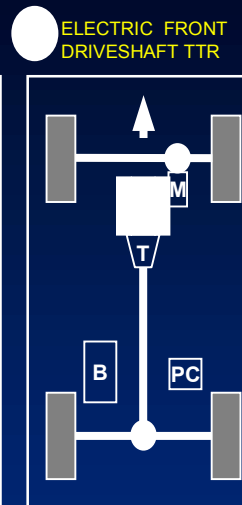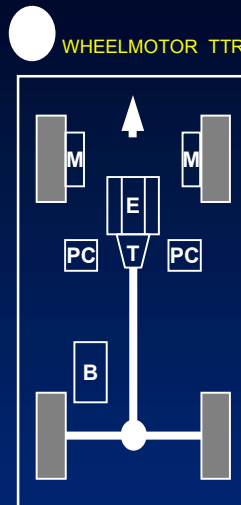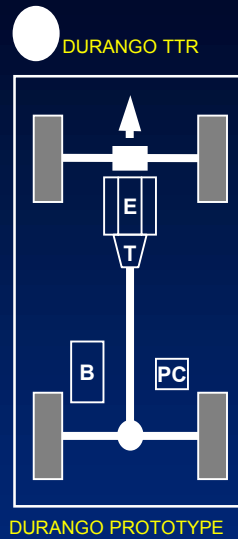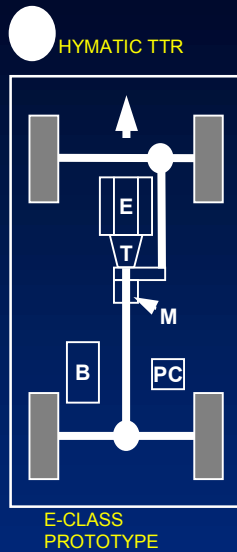
Component Selection

- Engine - Trailer Towing and Gradibility
- Motor - 0 to 60, 40 to 60 MPH Acceleration
- Battery - Reserve Capacity for Cold Weather Performance (and Power Generation)
- Final Drive Ratio - Fuel Economy and Driveability
- Cooling System - Operating at Extreme Temp.
- Sensitivity Studies - Weight, Aerodynamic, Rolling Resistance, Brake Drag, etc.

HEV Component Packaging
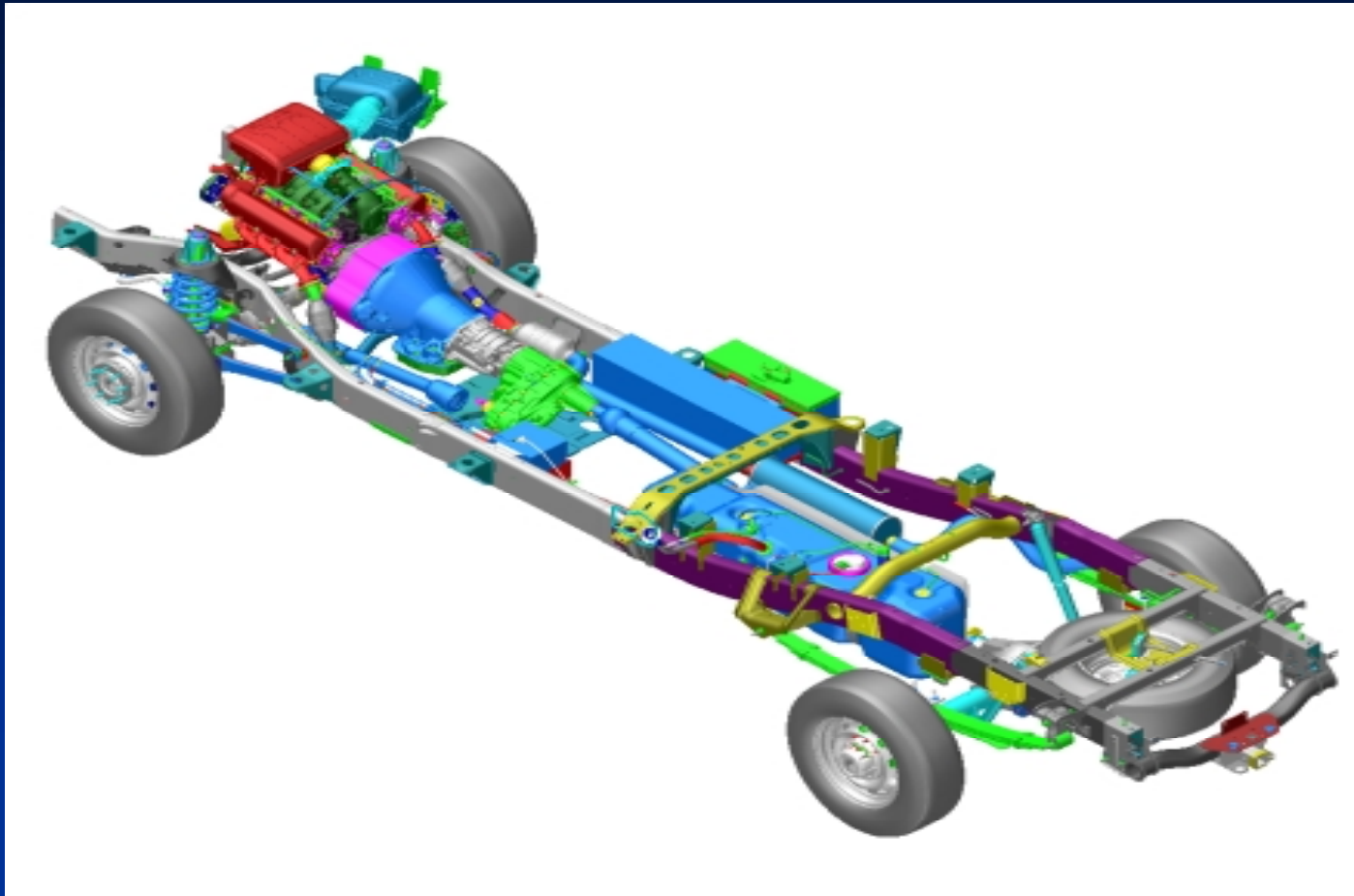
HEV Control Strategy Examples

PARALLEL HYBRID

- Electric Assist Mode

- Electric Cruise Mode

- etc.
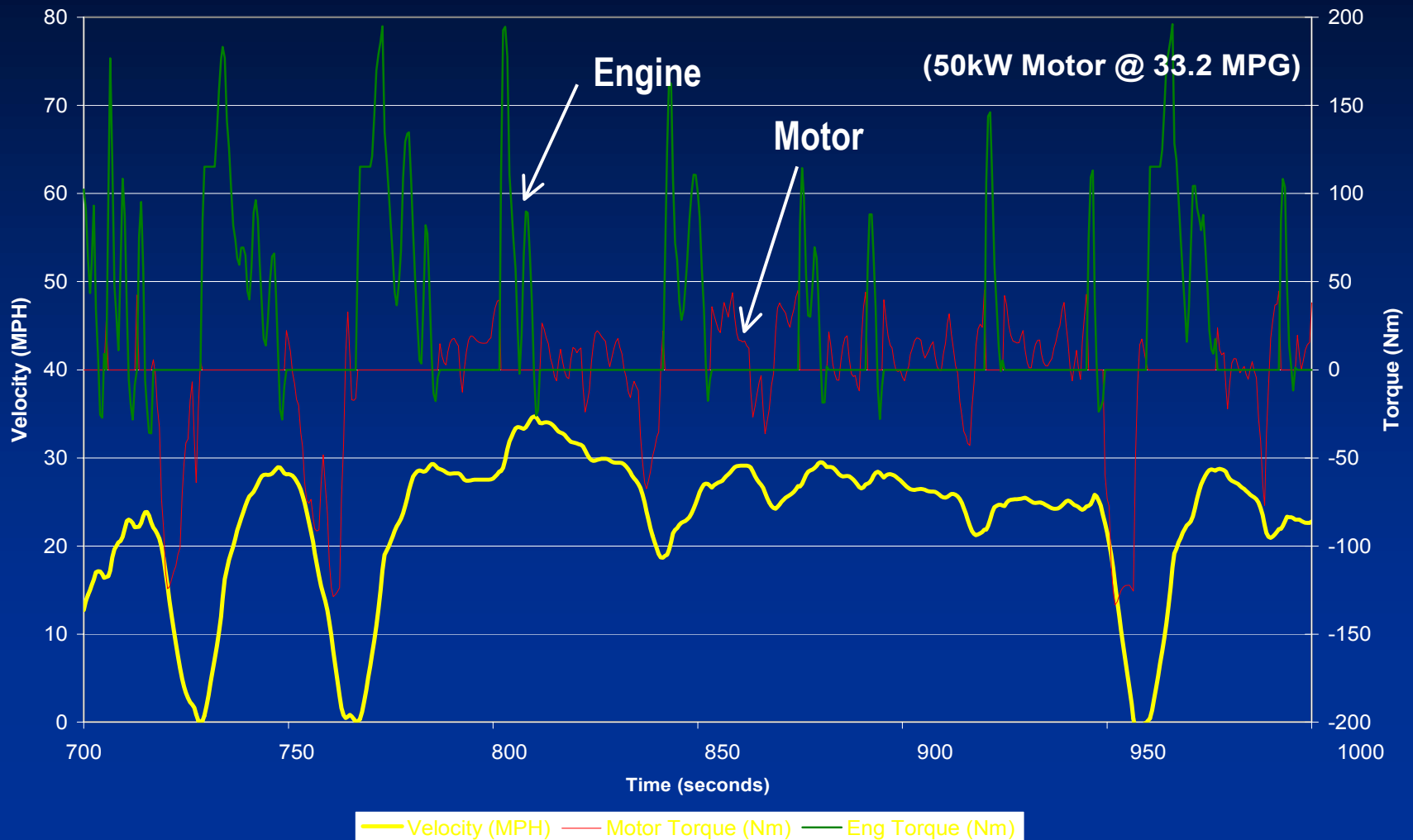
HEV Control Strategy Dimensions

- Transmission Shift Schedule
- Torque Converter Lock-Up Schedule
- Motor Torque Management
- Engine Torque Management
- Coast Down Regen / Regen Braking
- Decel Fuel Shutoff
- Stop/Start

Drive Cycle Requirements

EPA City Cycle

EPA Highway

Digital Functional Vehicle

HEV Functional Objective

- Reduce engine from 3.8L V6 to 2.4L I4 while maintaining the V6 performance.
  - ✓ 0-60 MPH = 11.2s
  - ✓ 40-60 MPH = 5.5s
  - ✓ 1/4 mile time = 18.3s
  - ✓ 1/4 mile speed = 77 MPH

- Increase Combined Fuel Economy $\geq$ 30%.
  - ✓ Conventional (City/Hwy/Comb) = 17/24/23 MPG

- Optimize control to take advantage of hybrid architecture.

Components Used for HEV Model

- Body: Dodge Caravan LWB
- Hybrid System: Through -The - Road (TTR)
- Engine: 2.4L I4, 96 kW SI Engine, Auto-4, FWD
- Motor: 32 kW (53 kW Peak) PM Motor, RWD
- Transmission: Four Speed Automatic
- Battery: Li-Ion 6 Ah, 72 Cells (260 V nom.)
- Performance Weight: 2533 kg (5585 lbs.)
  - 2268 kg curb + 136 kg passenger + 129 kg hybrid

Optimization Problem Definition

- Maximize Composite Fuel Economy
- Constraints
  - delta SOC < 0.5%
  - delta trace < 2 mph

Fuel Economy (mpg)

- Parameters
  - Charge Torque
    - engine torque request = driveline request + charge torque
    - maybe negative and is scaled by SOC
  - Electric Decel Speed
    - Speed below which engine is allowed to shutdown during a decel event
  - Low SOC setpoint
    - desired lowest state of charge
  - High SOC setpoint
    - desired highest state of charge

Approach

- Step 1
  - Central Composite Design of Experiments
- Step 2
  - Sequential Quadratic Programming using the approximation developed in Step 1 starting from estimated optimum
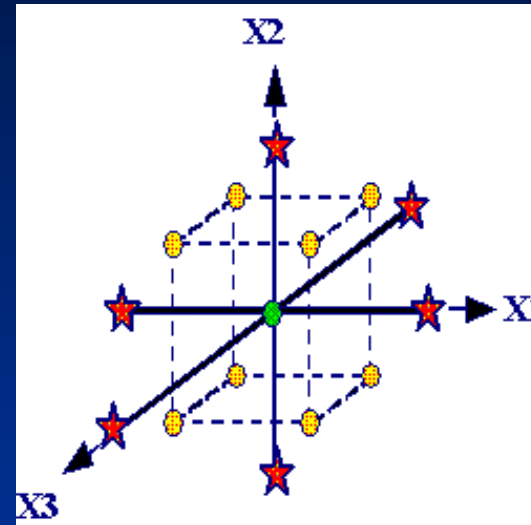
Optimization Results

- Performed 31 function evaluations (~190 minutes) including 25 evaluations in the DOE
- Fuel economy improved from 23.3 to 37.2 (~58 % change)

+ 3 %

37.2 mpg
Opt. Hybrid

36.2 mpg
Hybrid

+ 55 %

23.3 mpg
Conv.
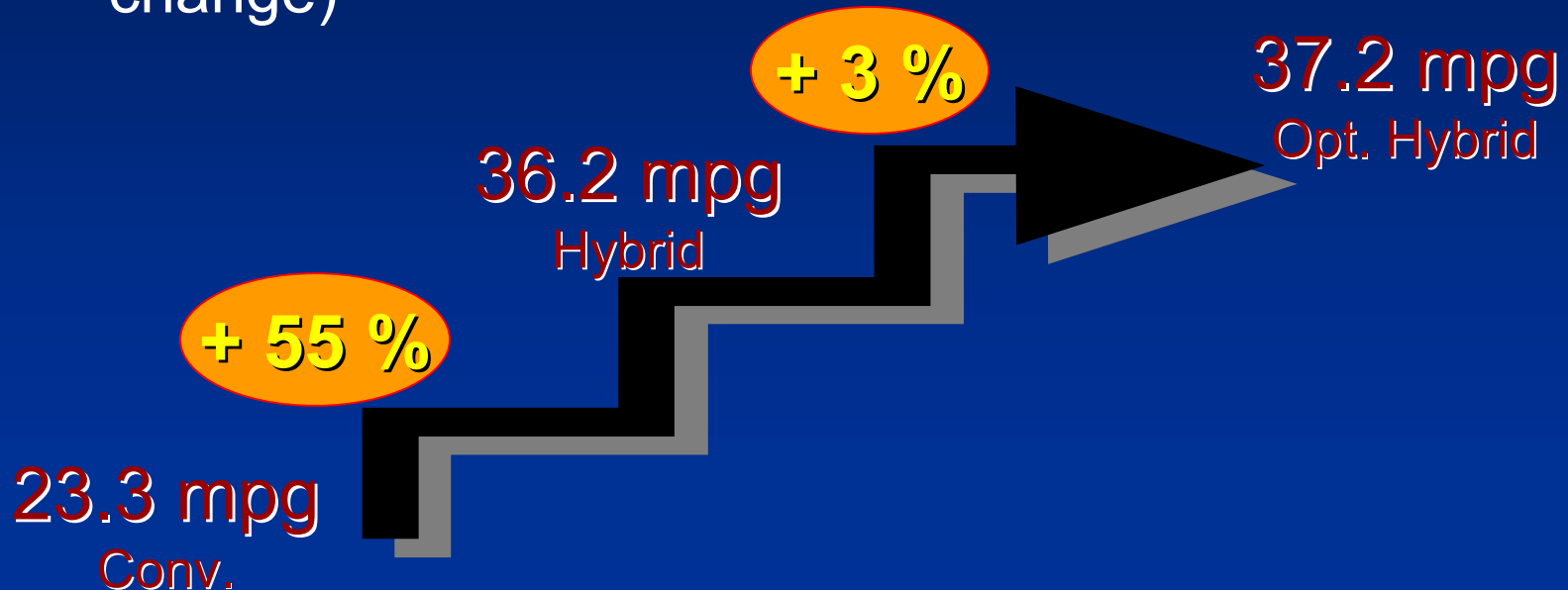
Conclusions and Future plans

- Hybridization provided significant fuel economy improvement compared to conventional
- Optimization of control strategy was able to provide some improvement in fuel economy
- Example connection provides ADVISOR users with the ability to perform optimization and experimental analysis

- Based on connection between ADVISOR and iSIGHT we plan to connect iSIGHT and many other models to include other design dimensions
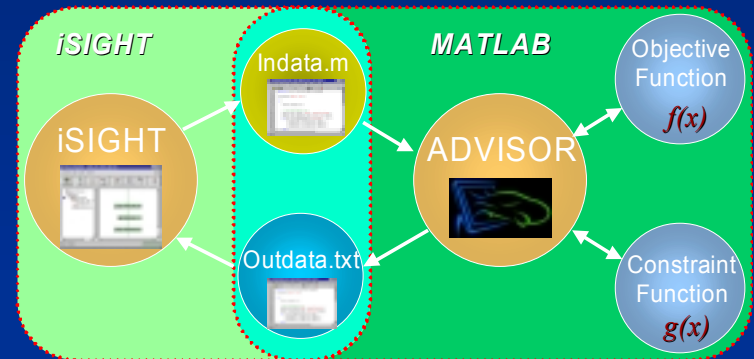
Why Derivative-Free Algorithms?

Advantages

- Do not require derivatives so work well for noisy data.
- Often have a global scope—do not get caught in local minima.

Disadvantages

- Can be slow to converge, especially for higher dimension problems.

Examples:

- Evolutionary algorithms
- Simulated annealing
- Lipschitzian-based optimization (like DIRECT)

Derivative-Free Algorithms in Study

DIRECT (DIvided RECTangles)

- Deterministic algorithm, searches design space by dividing it into rectangles and sampling center points.
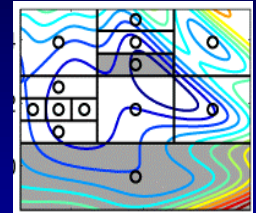
Simulated Annealing (SA)

- Stochastic algorithm, searches in random steps from an initial point, accepting or rejecting new points according to a "cooling schedule."
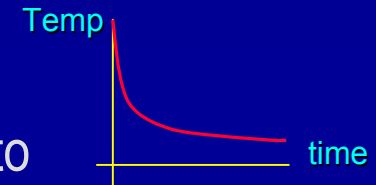
Evolutionary Algorithm (EA)

- Starts with random initial "population" of designs, keeps best designs (natural selection) and uses them to generate new population (by mutation, cross-breeding).

Comparison Method
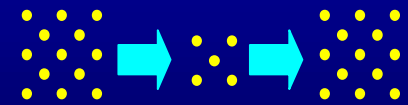
Metrics to Compare:

- Rate of objective function improvement (vs. number of function calls).

  - Function evaluations used as metric because time to run algorithm code insignificant compared to time for one function call (milliseconds *vs.* 30 sec to 1 minute).

- Best point found after 500 function evaluations.

ADVISOR 3.0

- Used "no-GUI" functionality for ease of implementing optimization.

- Nominally, optimizing a parallel hybrid with PNGV constraints.

- Work will most likely apply to PSAT as well (some work done with DIRECT and PSAT 4.0).

electric motor

IC engine

battery pack
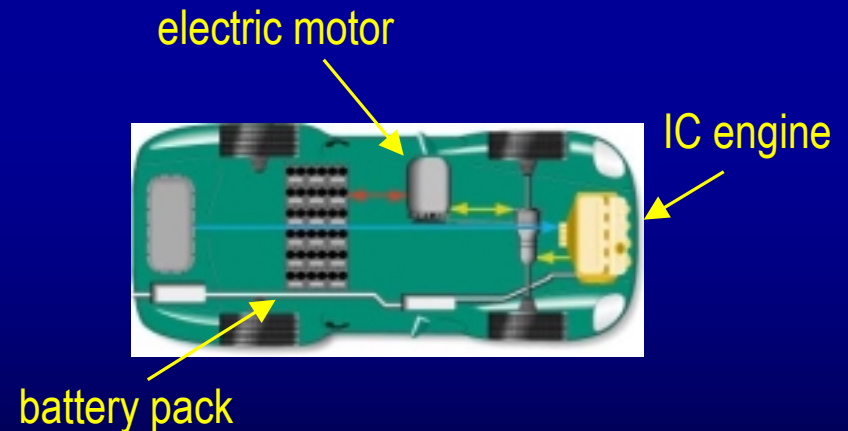
parallel hybrid

HEV Test Problem

- Simple, 3-variable problem using Advisor 3.0:

Maximize	Composite Fuel Economy (highway and urban)

Constraints

0-60mph time	<= 12 sec
0-85mph time	<= 23.4 sec
40-60mph time	<= 5.3 sec
Max. launch grade	>= 30 %
Max. grade @ 55mph	>= 6.5 %
Max. speed	>= 85 mph
Max. acceleration	>= 0.5 g
5 sec. distance	>= 140 ft
Delta state of charge	<= 0.005 %

Variables

Engine power
Motor power
Battery size

1. Rate of objective function improvement:
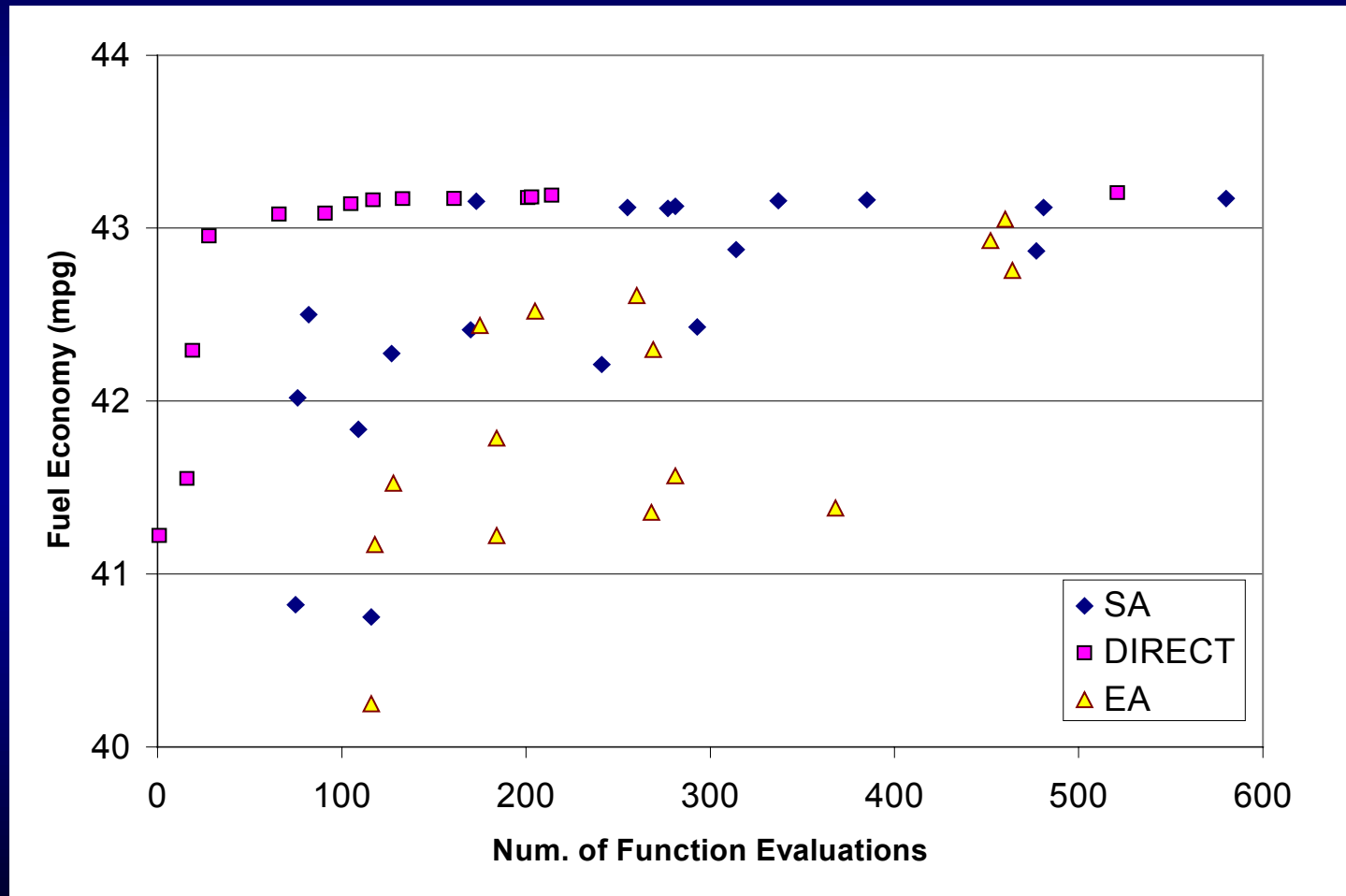
2. Best overall point found after 500 function evaluations:

Algorithm	Objective Function	Engine Power	Motor Power	Battery Size
DIRECT	43.20	41.08	42.92	28.00
SA	43.18	41.81	42.28	27.59
EA	43.05	39.07	45.40	29.28

Summary:

- DIRECT and SA found approximately the same best point.

- EA found a nearby point (motor and battery slightly larger, engine smaller).

Problems with DIRECT

High Dimensionality:

- For problems of 10 variables or larger, DIRECT has difficulties because of the systematic way it searches the design space.

Wide Variable Ranges:

- DIRECT has too many divisions to make along a single variable if the range of that variable is quite wide.

Slow Local Convergence:

- Points near minima are found quite rapidly, but because of DIRECT's global searching, it has difficulty zeroing in on minima.

Generalized Decomposed Method

- When initial search with DIRECT plateaus, randomly select 2-3 of the variables for a subproblem.

- Run the subproblem until it plateaus, select new subproblem from unchosen variables.

- Iterate until set number of "cycles" complete.

Advantages

- "Generalized" means that subproblem variables are chosen randomly—user doesn't need to know structure of problem.

- Eliminates dimensionality problem.

Disadvantages

- Coupled variables may not be chosen for same subproblem.

- Possibility of missing the global optimum.

- Adds parameters to tune. ☹

Sequential Method

- Again, when initial search with DIRECT plateaus, shrink variable bounds (to ~10% of original) and rerun problem.

- Run the new problem until it plateaus, again shrink variable bounds (to ~1% of original) and rerun problem.

- In general, stop after this second rerun.

Advantages

- Zeroing in on optimum with variable bounds helps DIRECT converge to an optimum.

- Two-step reduction allows for some semblance of globality to remain.

Disadvantages

- Significant possibility of losing global optimum (however, by the time DIRECT first plateaus, it is often in the area of the global optimum).

- Adds parameters to tune. ☹

- ## Hock & Schittkowski Test Problem #105

  - ### 8-variables

  - ### Nonlinear objective function, with added sine term for "noise"

  - ### One linear inequality constraint

  - ### Simple bounds on variables

- ## Hock & Schittkowski Test Problem #110

  - ### 10-variables

  - ### Nonlinear objective function, with added sine term for "noise"

  - ### Simple bounds on variables
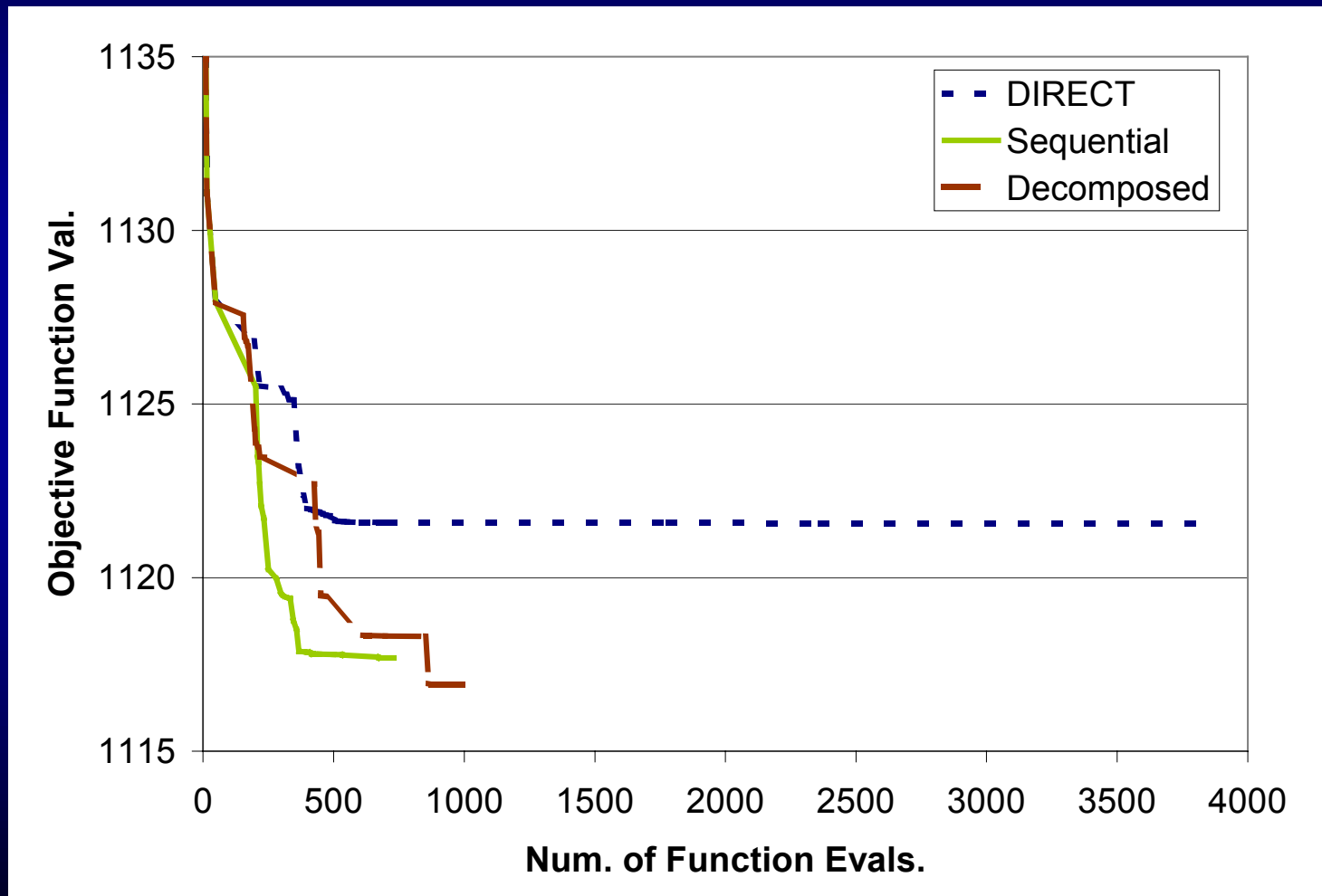
1. Rate of objective function improvement:

2. Best overall point found:

Algorithm	*f(x)* at Optimum	Func. Eval. # when Optimum Found
DIRECT	1121.558	3840
Sequential	1117.682	731
Decomposed	1116.913	874

Summary:

- Both improvement methods had a better rate of objective function improvement.

- Sequential Method and Decomposed Method found better points than DIRECT (DIRECT probably found nearby local optimum).
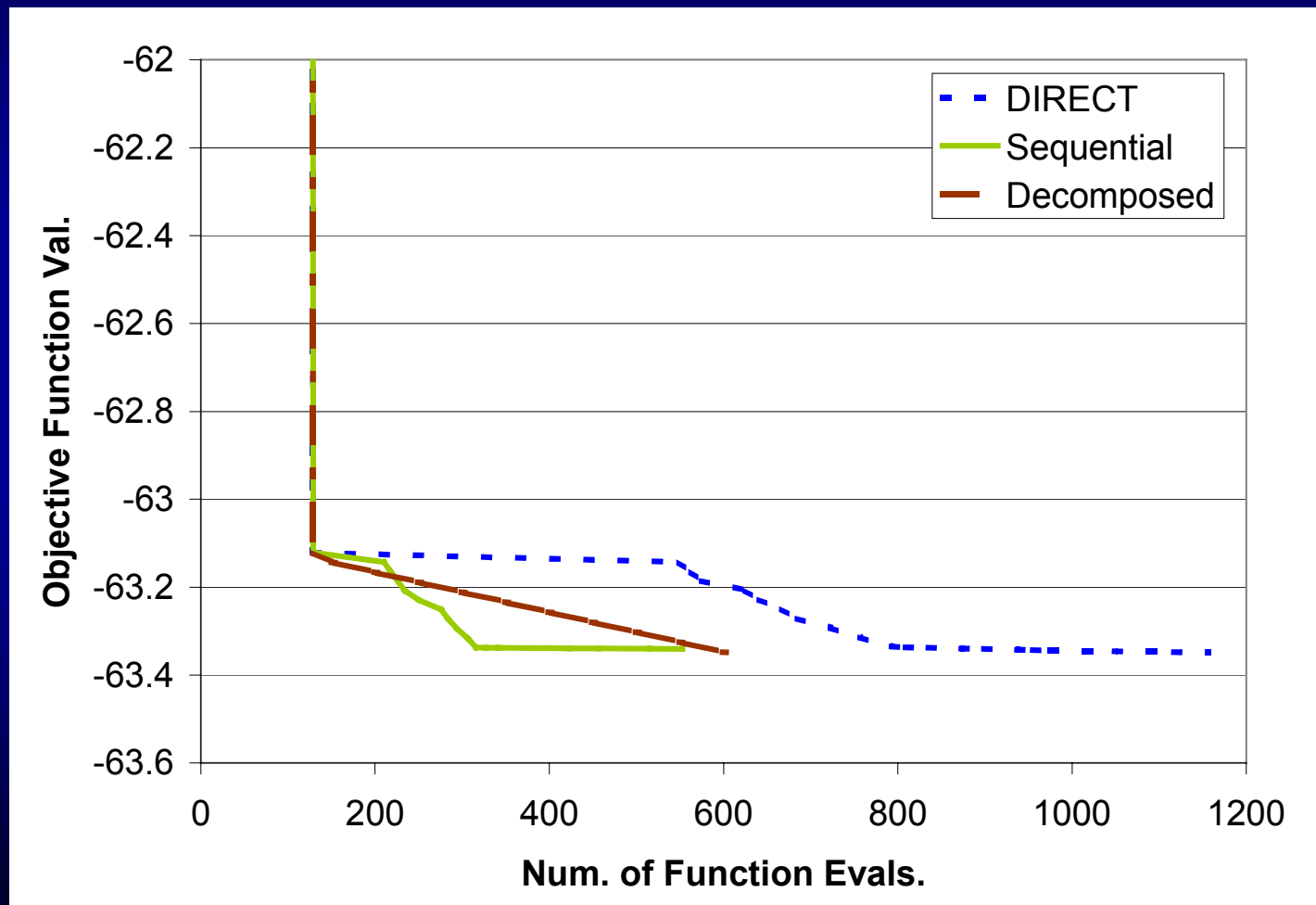
1. Rate of objective function improvement:

2. Best overall point found:

Algorithm	*f(x)* at Optimum	Func. Eval. # when Optimum Found
DIRECT	-63.3488	1157
Sequential	-63.3403	553
Decomposed	-63.3488	603

Summary:

- Both improvement methods had a better rate of objective function improvement.

- All methods found approximately the same point.

Large HEV Test Problem

Maximize   Composite Fuel Economy (highway and urban)

Constraints   Same performance constraints as before

Variables   Engine power
                   Motor power
                   Battery size
                   Final drive ratio
                   Min. SOC allowed
                   Max. SOC allowed
                   Charge torque
                   Min. torque fraction
                   Off torque fraction
                   Electric launch speed

Energy Control
Strategy Variables
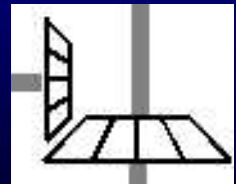
1. Rate of objective function improvement:
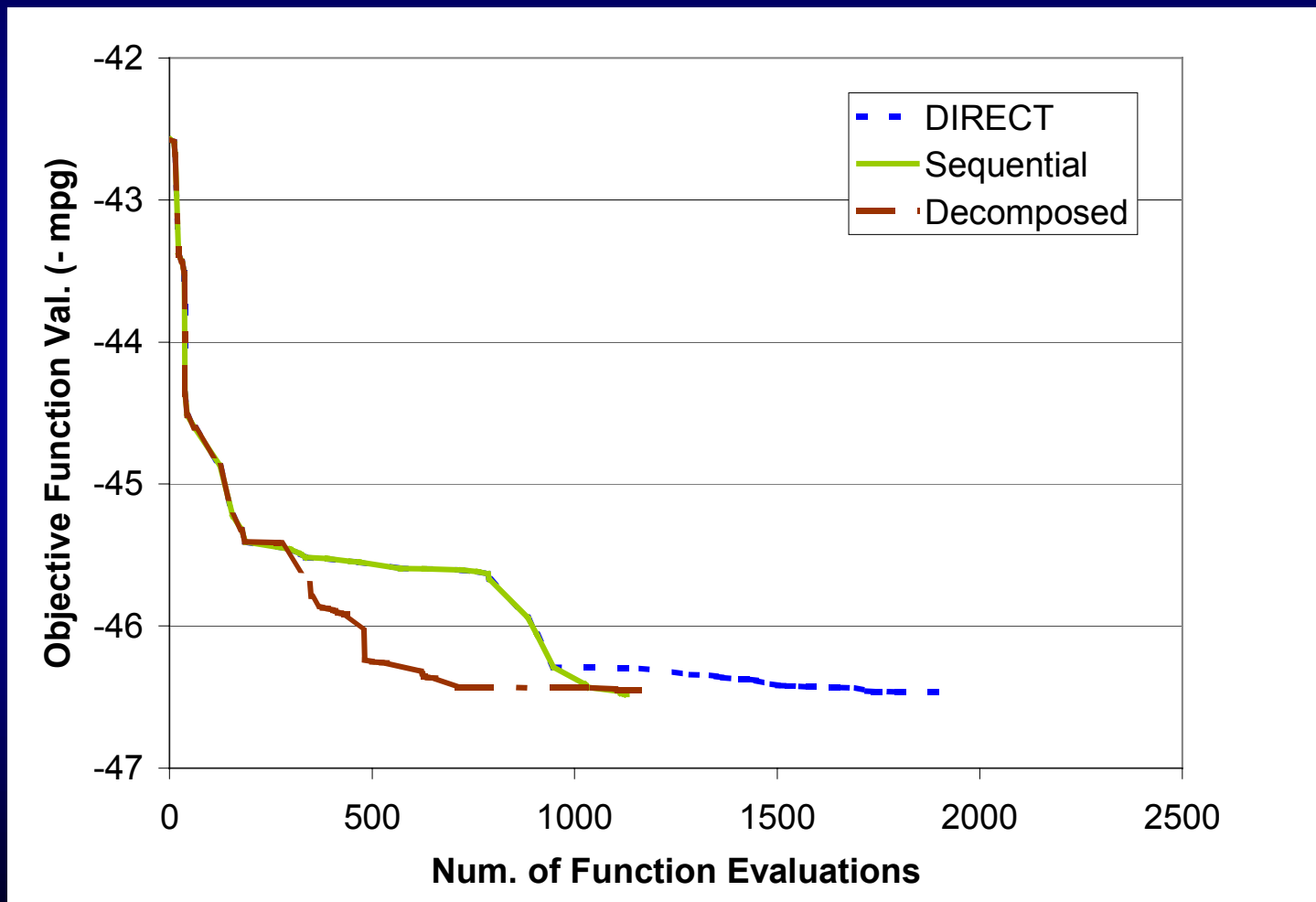
2. Best overall point found:

Algorithm	*Objective Function Value at Best Point Found*	Func. Eval. # when Best Point Found
DIRECT	46.465	1912
Sequential	46.483	1129
Decomposed	46.464	1159

Summary:

- Both improvement methods had a *significantly* better rate of objective function improvement.

- All three methods found approximately the same "best" point.

Conclusions

- Both improvement methods performed better than DIRECT on both test problems and the ten-variable HEV problem.

- These two methods improve on DIRECT's dimensionality and local convergence problems.

- These methods will offer significant time savings for optimization with PSAT as well.

- The possibility of missing the global optimum has not been observed with these two methods.

Acknowledgements

This work was presented in a Master's thesis and funded by the National Renewable Energy Laboratory. Special thanks to Tony Markel for his help with ADVISOR.

DELPHI
Automotive Systems

Energenix Center

Co-Simulation of Electrical and Propulsion Systems using ADVISOR and Saber

A Solution for Total Vehicle Energy Management Simulation

John MacBain, Joseph Conover, Valerie Johnson

August 28, 2001

Co-Simulation of
ADVISOR and Saber

- ◆ Traditional Electrical Simulations

- ◆ Co-Simulation Concept

- ◆ Implementation of Co-simulation for Saber and ADVISOR for Traditional Vehicles

- ◆ Demonstration of Co-simulation

Co-Simulation of
ADVISOR and Saber

◆ Electrical architecture simulation has traditionally been independent from the propulsion system of the vehicle

◆ Increasing electrical power budgets in traditional vehicles (EVA, EPS, catalytic converter heating, etc.) make consistent solution of the propulsion and electrical systems necessary for accurate results (mpg, sizing of electrical components, macro power flow, etc.)

◆ Hybrid architectures effectively marry the electrical and propulsion system, making them inseparable from a computational standpoint

Co-Simulation of
ADVISOR and Saber

A Possible Solution

◆ Potentially Ideal solution - model electrical system in MatLab/Simulink as a part of ADVISOR

◆ Challenges with the ideal solution
  – Saber and other packages already are developed and focused on the solution of the electrical system
  – Many automotive OEMs are committed to Saber for electrical system analysis
  – Many component models have already been developed in Saber and not in MatLab
  – Saber imports Pspice models

◆ Thus, it makes sense to connect existing specialized tools rather than re-inventing the wheel

Co-Simulation of
ADVISOR and Saber
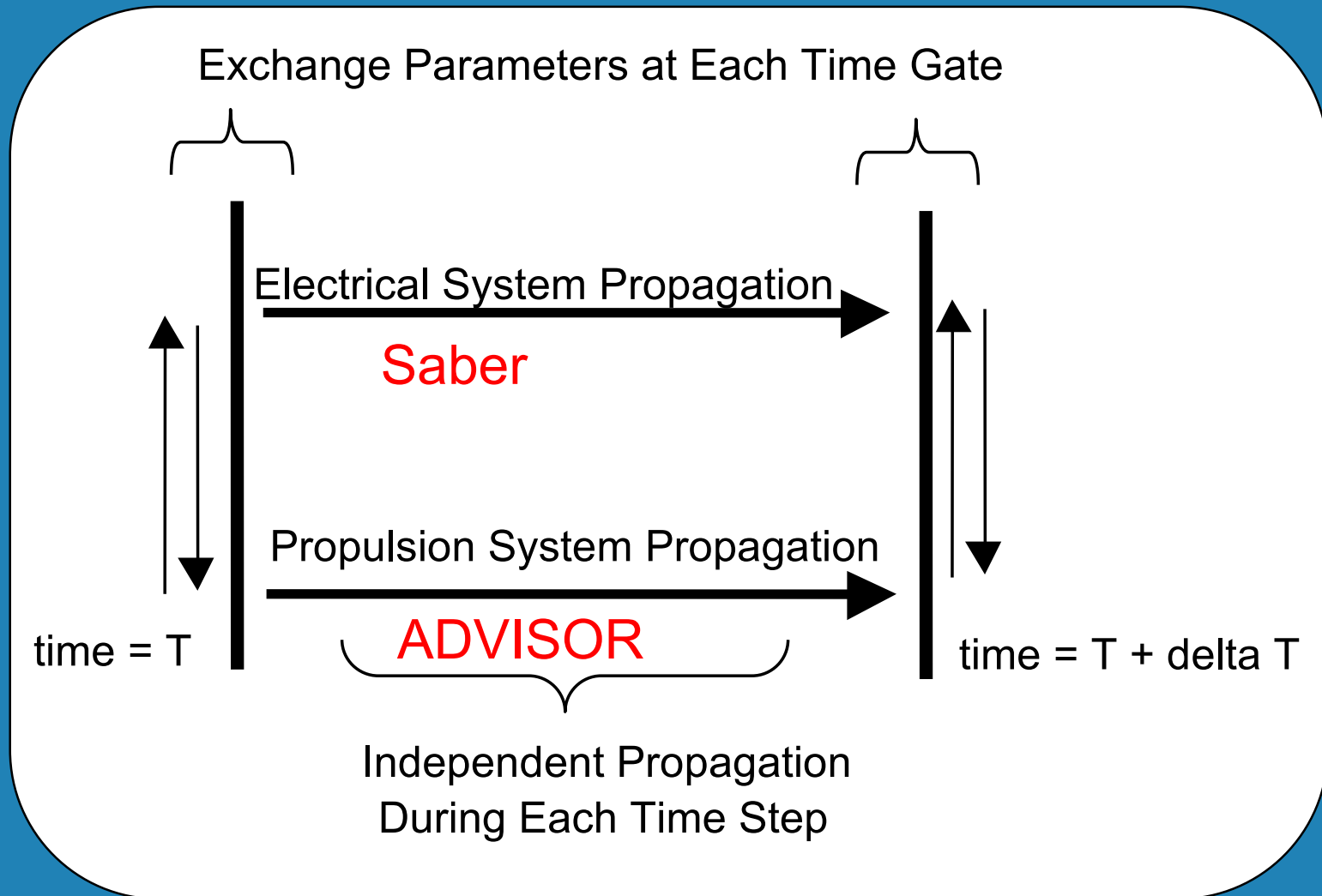
Potential Parameters to Pass:

ICE instantaneous rpm
Generator instantaneous required shaft torque

Exchange Parameters at Each Time Gate

Electrical System Propagation

Saber

Propulsion System Propagation

ADVISOR

time = T

time = T + delta T

Independent Propagation
During Each Time Step

Co-Simulation of
ADVISOR and Saber

Co-Simulation of
ADVISOR and Saber

Co-Simulation of
ADVISOR and Saber

With this screen you can select single or dual voltage schematics.

Co-Simulation of
ADVISOR and Saber

Co-Simulation of
ADVISOR and Saber

Periodic Load Switching
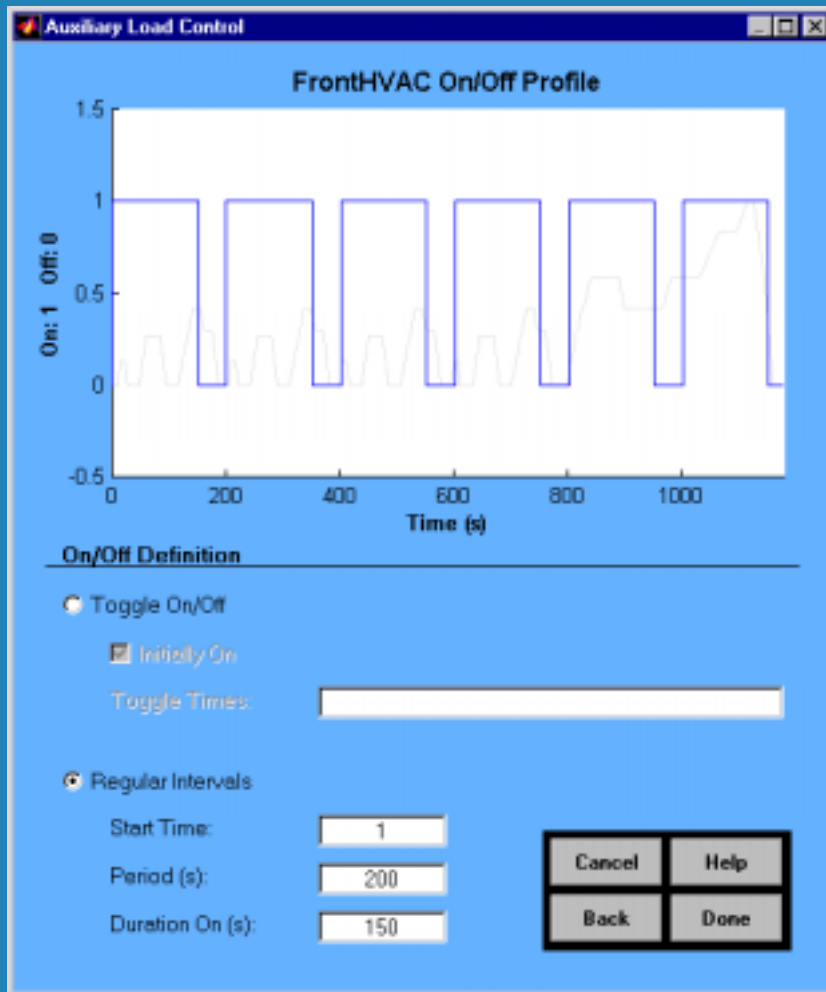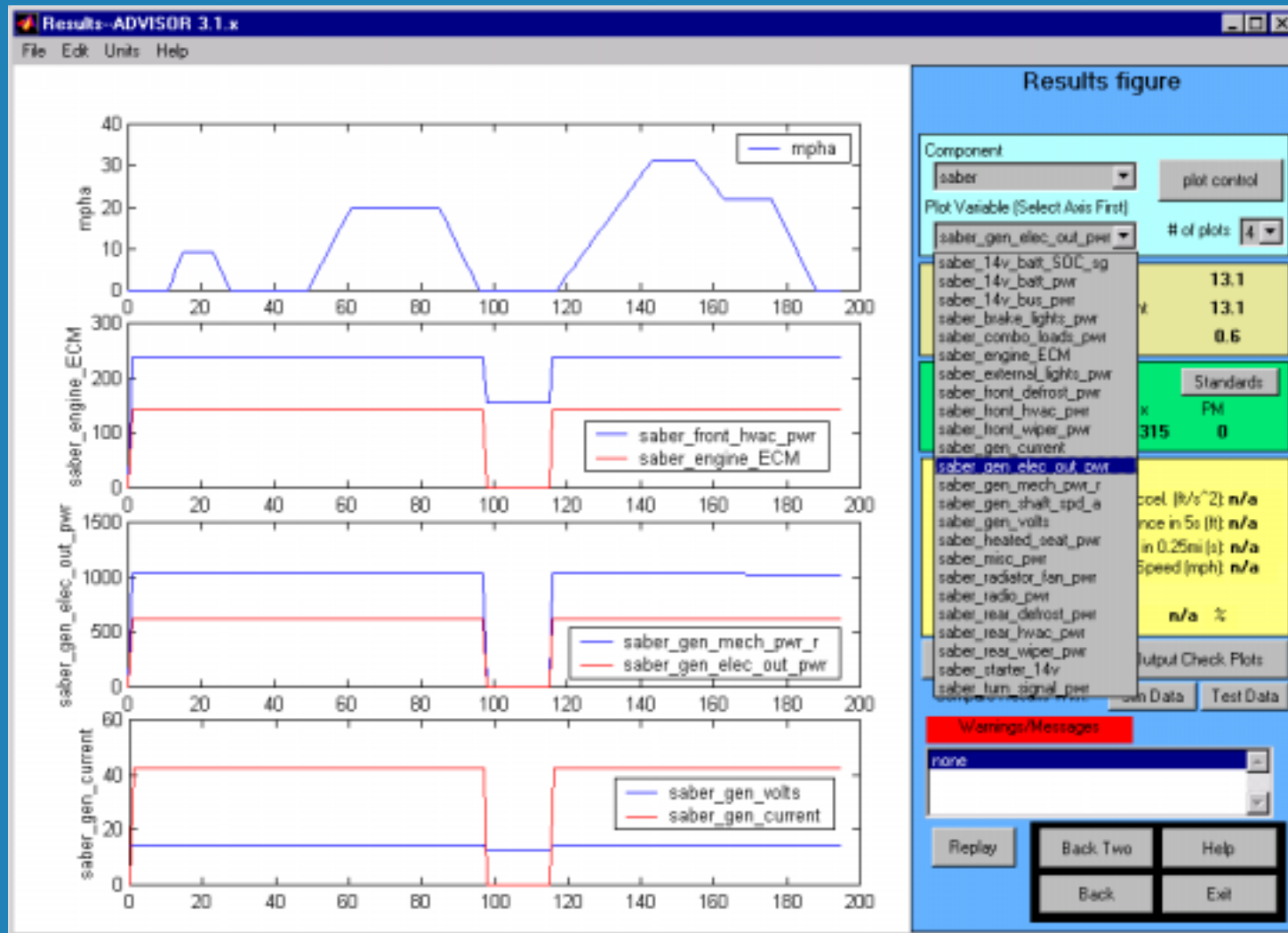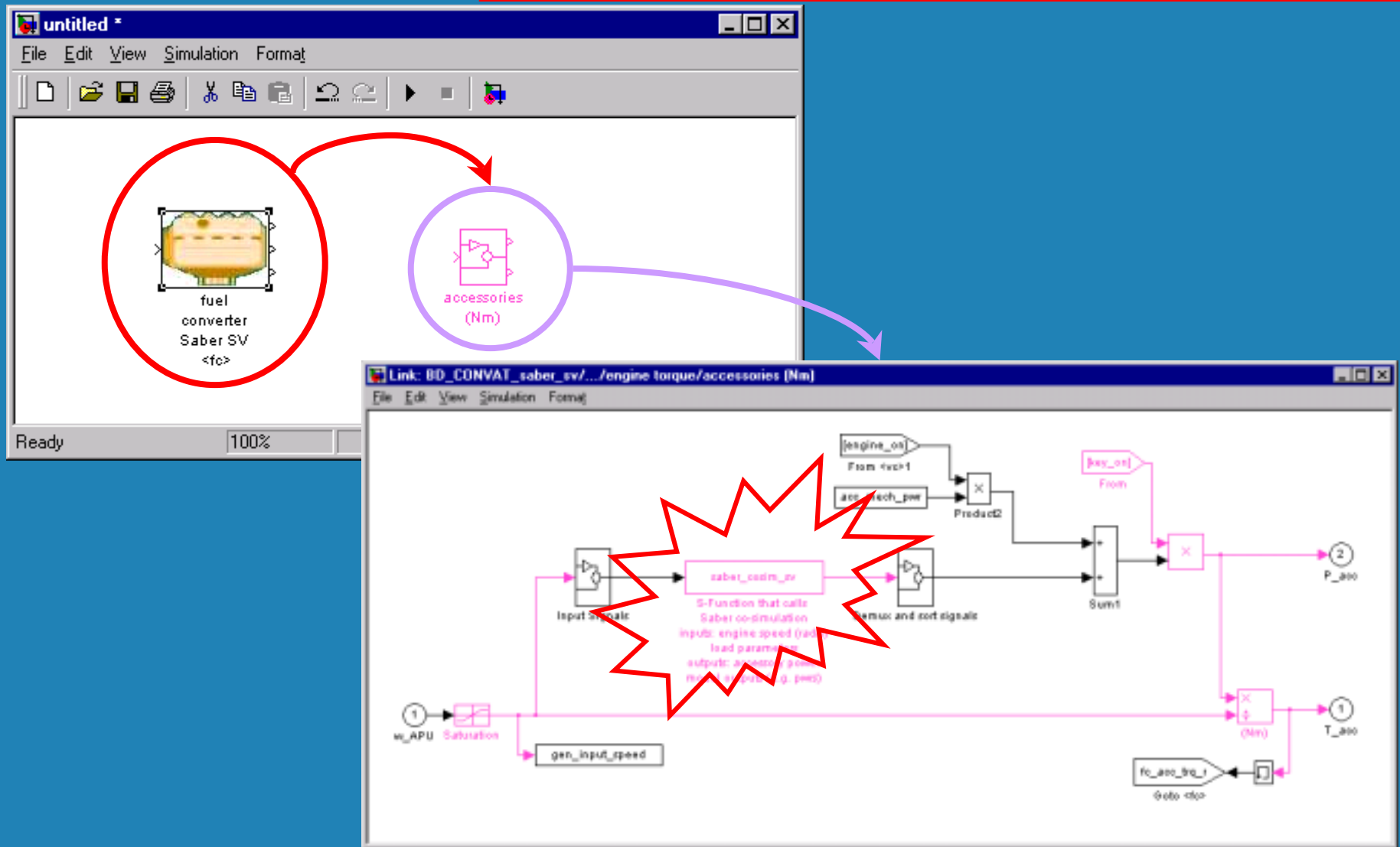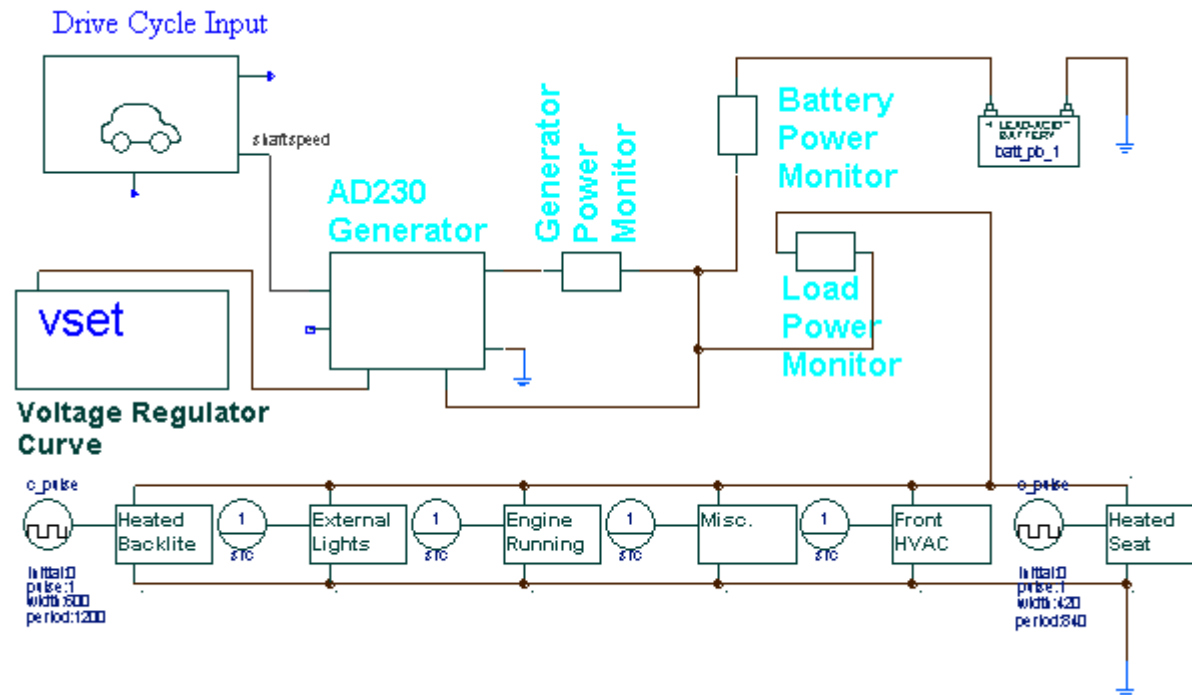
Co-Simulation of
ADVISOR and Saber
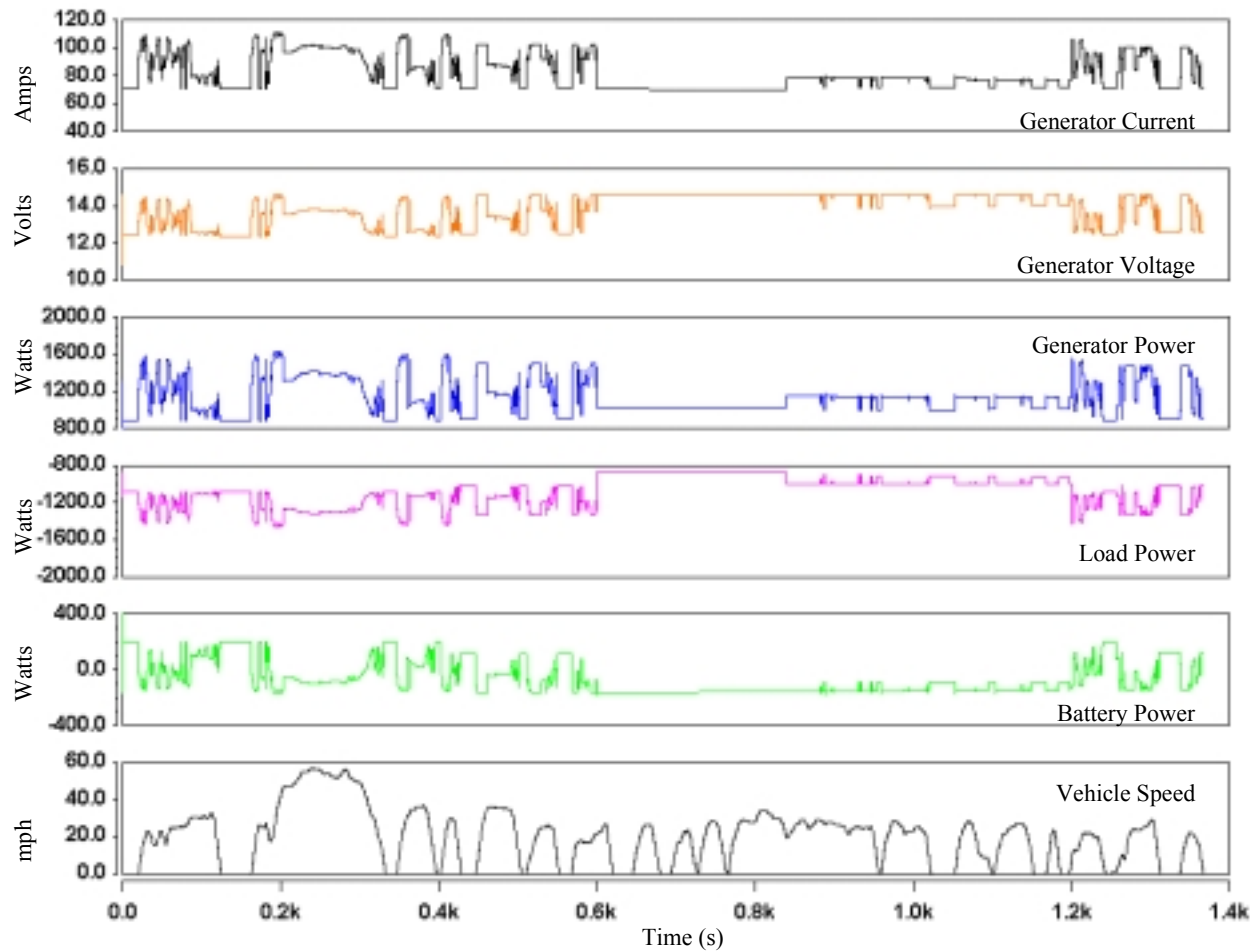
External lighting
Defroster
Engine Control
Misc loads

Heated Rear Defroster

Heated Seats

t(s)

Co-Simulation of
ADVISOR and Saber

Co-Simulation of
ADVISOR and Saber
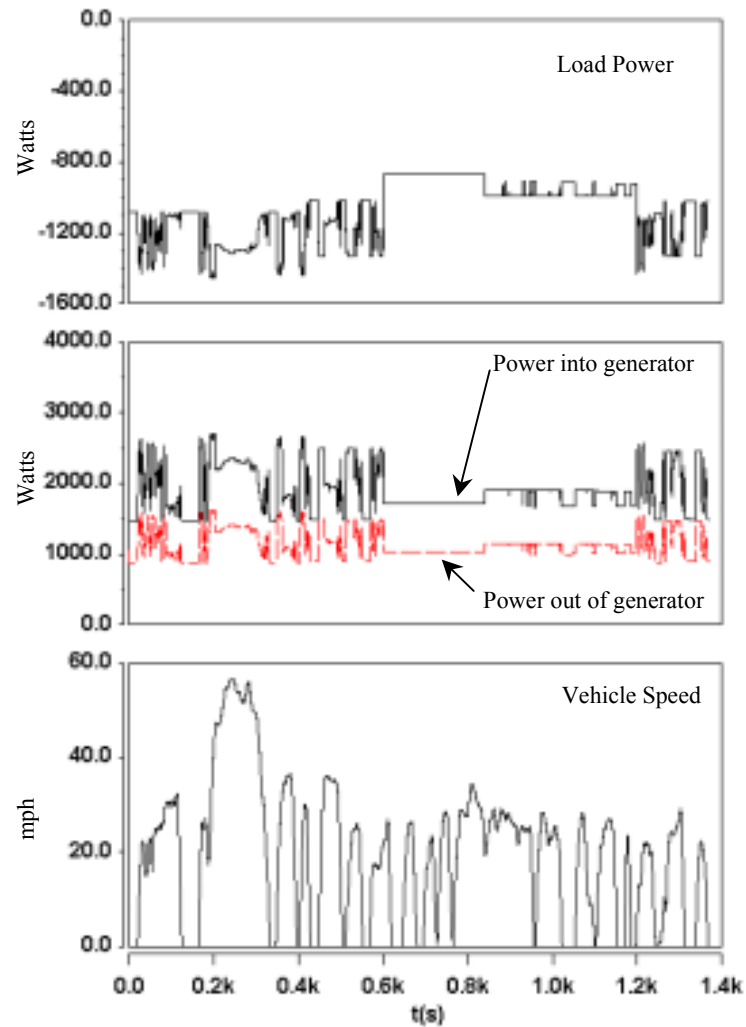
Co-simulation Demonstration:
Co-Sim MPG to Non-Co-Sim Simulations

Engine Accessory Load (Watts)	Drive Cycle		
	UDDS	HWY	FTP-75
500	18.04	33.70	18.85
1000	17.69	32.93	18.50
1500	17.47	32.28	18.32
2000	17.09	31.65	17.92
2500	16.71	30.95	17.51
co-sim	17.02	31.42	???

Co-Simulation of
ADVISOR and Saber

Co-simulation Demonstration: Co-Sim MPG to Non-Co-Sim Simulations

Engine Accessory Load (Watts)	Drive Cycle		
	UDDS	HWY	FTP-75
500	18.04	33.70	18.85
1000	17.69	32.93	18.50
1500	17.47 8%	32.28 9%	18.32
2000	17.09	31.65	17.92
2500	16.71	30.95	17.51
co-sim	17.02	31.42	???

8% Spread

Co-Simulation of
ADVISOR and Saber
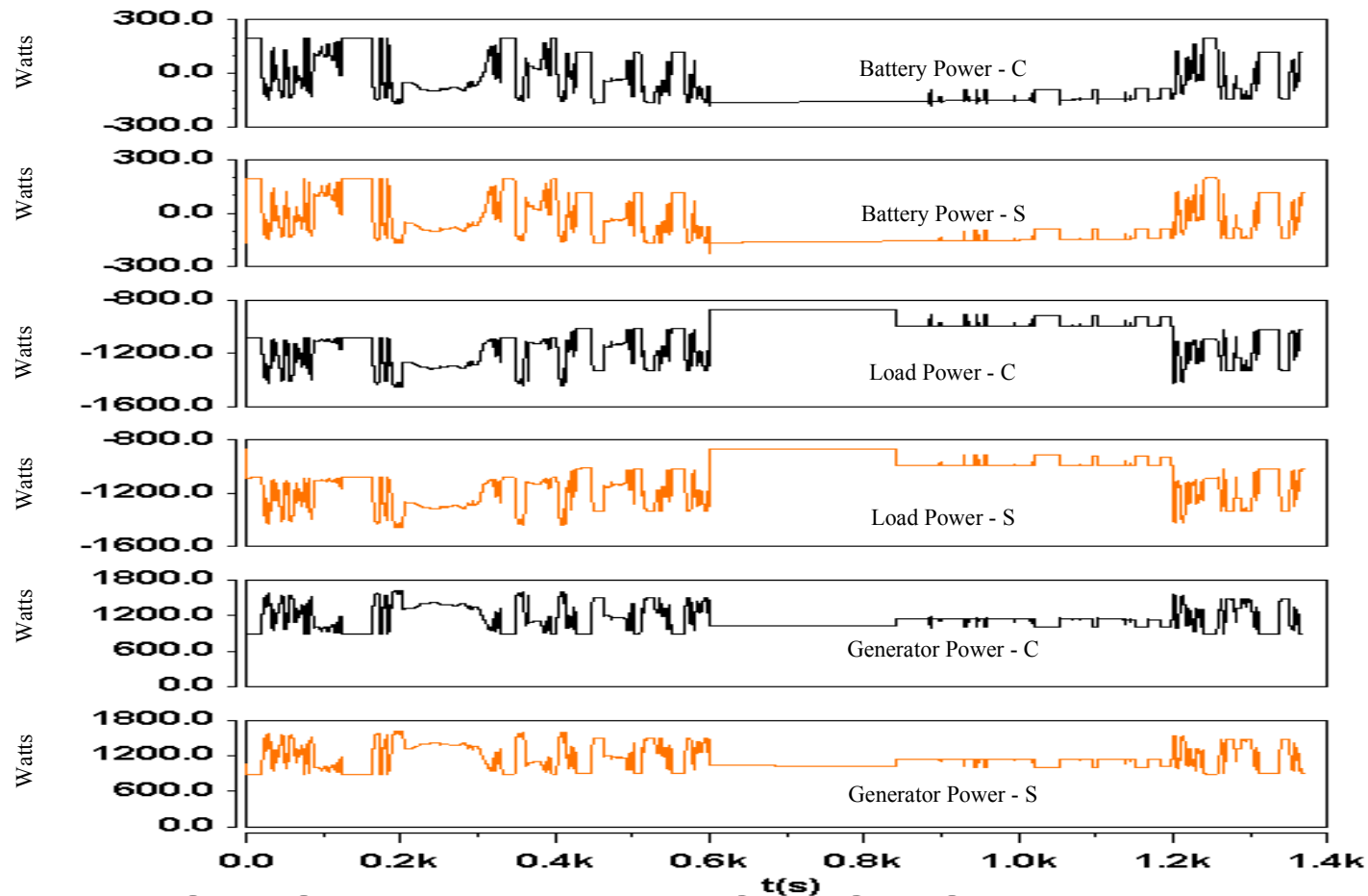
S = Saber alone   C = Co-Sim

Co-Simulation of
ADVISOR and Saber

◆ Co-simulation of Saber and ADVISOR has been established for traditional vehicles

◆ Co-simulation validates well against similar runs performed without co-simulation

◆ Co-simulation code will become available as a free download from NREL in the future

– Utilization will require licenses of MatLab/Simulink and Saber

◆ Co-Simulation code for series and parallel hybrids is being developed presently for future distribution

Co-Simulation of
ADVISOR and Saber

Model Development

Emissions Modeling with Artificial Neural Network

Csaba Tóth-Nagy, West Virginia University

Development of Transient Prius Engine Model Based Upon Neural Networks

Mike Duoba, Don Gray, Toma Hentea, and Mike Jakov,
Argonne National Laboratory

Emission Modeling with Artificial Neural Network

Csaba Tóth-Nagy

West Virginia University

Emission modeling

- Need for emissions modeling
- Present state: Emission maps
  - Lack of transients
- Artificial neural networks
  - Suitable for non linear systems

Project overview

- Emission data from engine test
- Train artificial neural network
- Engine speed and torque from ADVISOR
- Predict emissions using ANN
- Emission data from chassis dynamometer test
- Compare predicted and measured results

Emission data from engine test

Engine test cycles
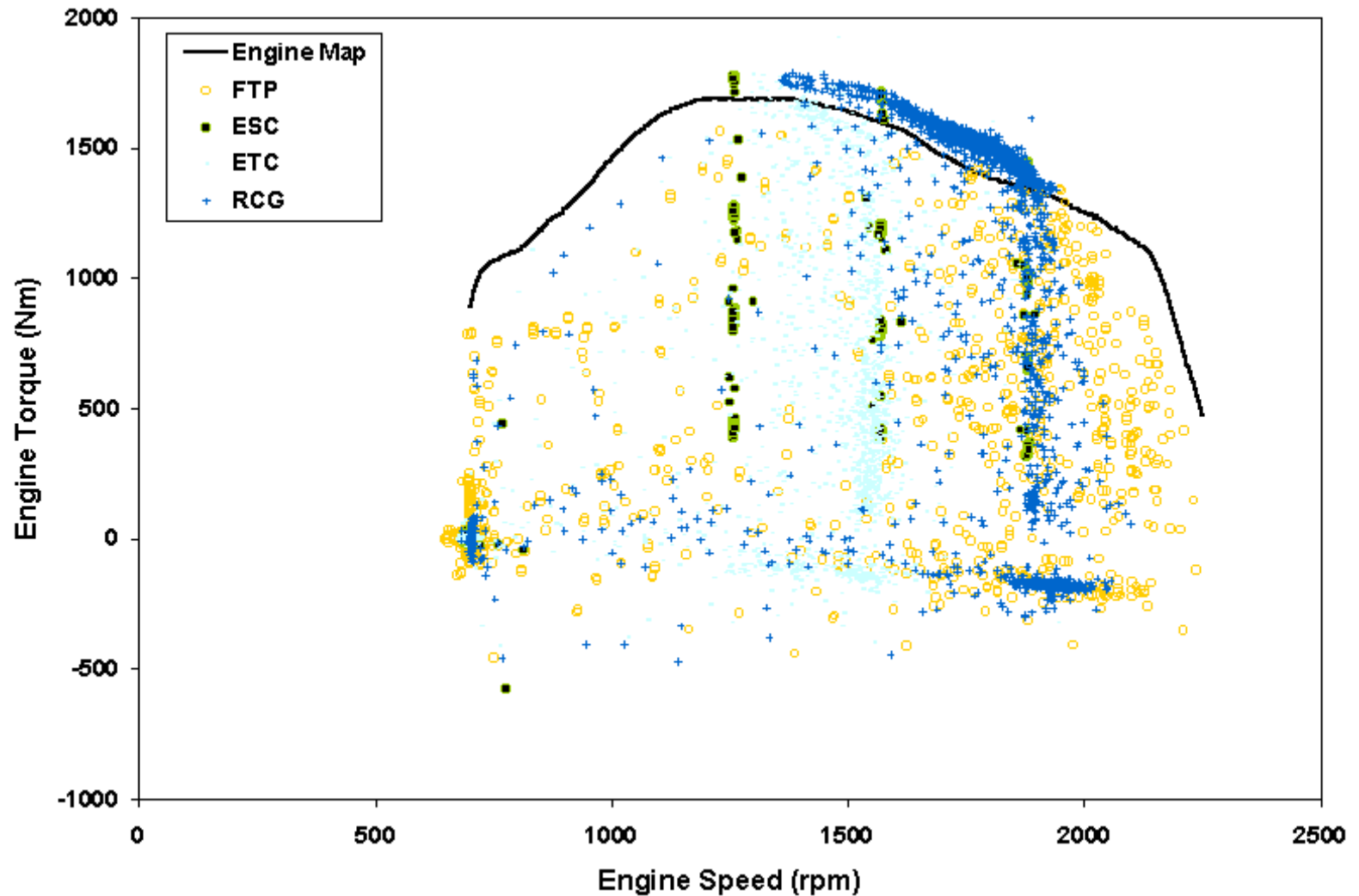
Artificial neural network
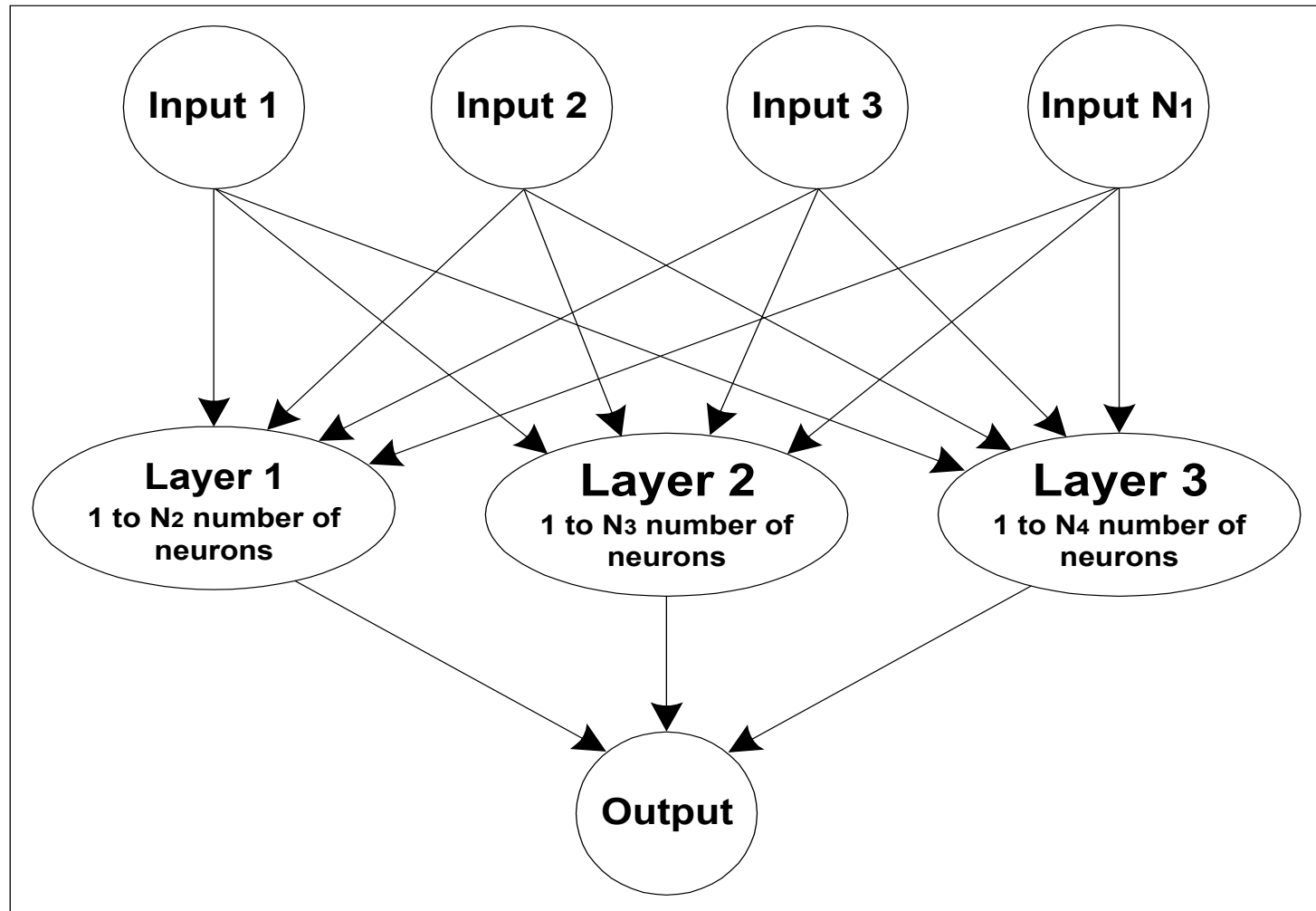
Artificial neural network (cont.)

- Input:
  - Speed, Torque, 1st and 2nd derivatives at 1, 5, 10 sec

- Output:
  - Emissions

Activation functions

Sine(x)

Tanh(x)

Tanh(1.5x)

Symetric Logistic
[y=2+(1/(1+exp(-x)))]

Output

Input
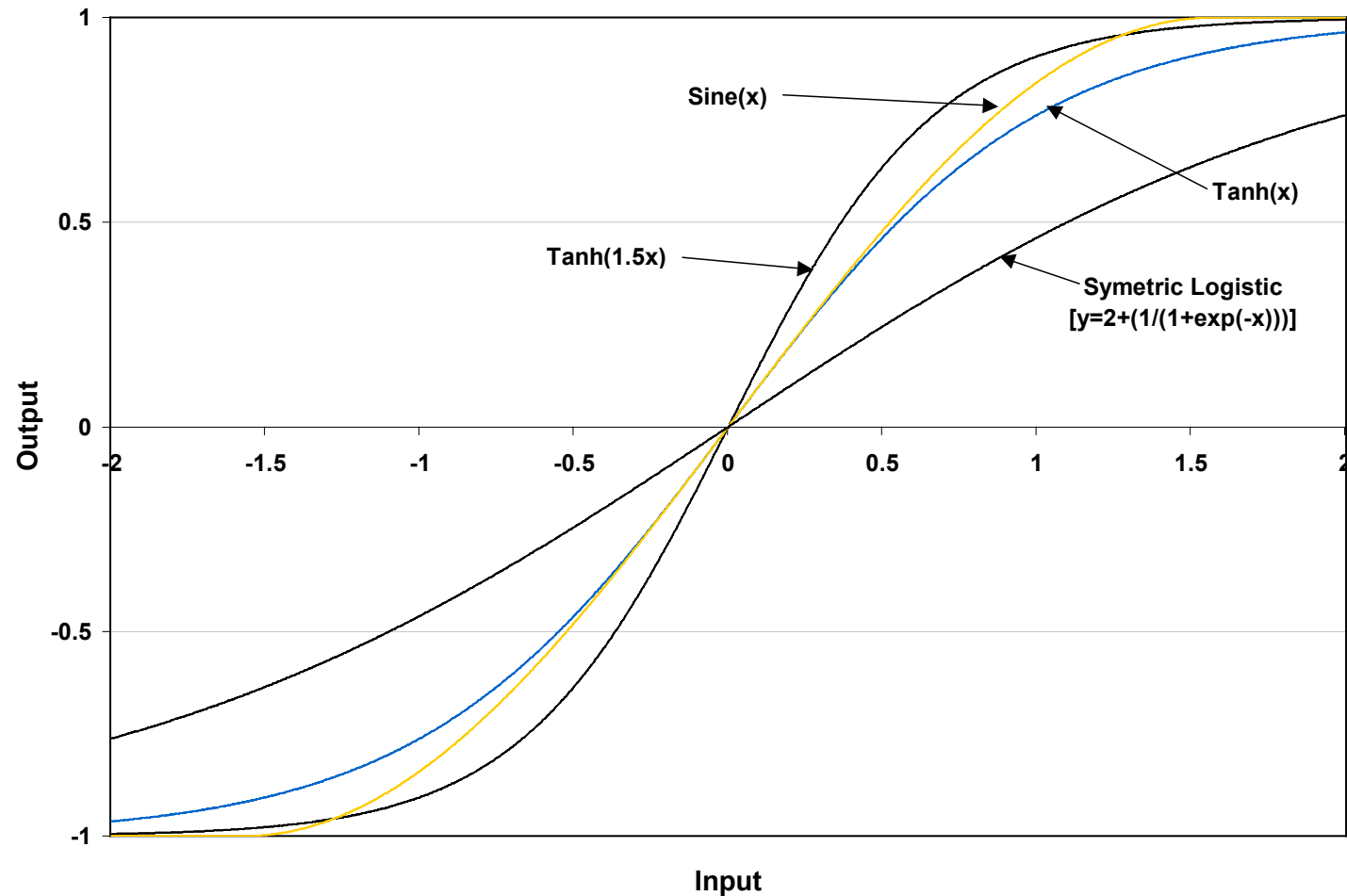
Integration into ADVISOR

- Driving schedule
- Component models
- Engine data
  - speed and torque
  - 1st and 2nd derivatives at 1, 5, 10 sec
- ANN model
- Predicted emissions

Vehicle chassis dynamometer test

The vehicles tested and simulated

Kenworth T800 Conventional Tractor Truck	
Engine	Cummins M-11
Coefficient of Drag	0.7
Frontal Area	8.5502 m^2
Rolling Resistance	0.0147
Mass	20,622 kg
Transmission	RTLO12610B
Type	10 - speed

Orion VI Hybrid Electric Bus	
Engine	DDC S30
Motor	300 kW DC Brushless
Battery Pack	27.3 kW-hr
Coefficient of Drag	0.79
Frontal Area	7.2413 m^2
Rolling Resistance	0.008
Mass	16,160 kg
Transmission	1 speed

CO$_2$ emission results from the conventional vehicle
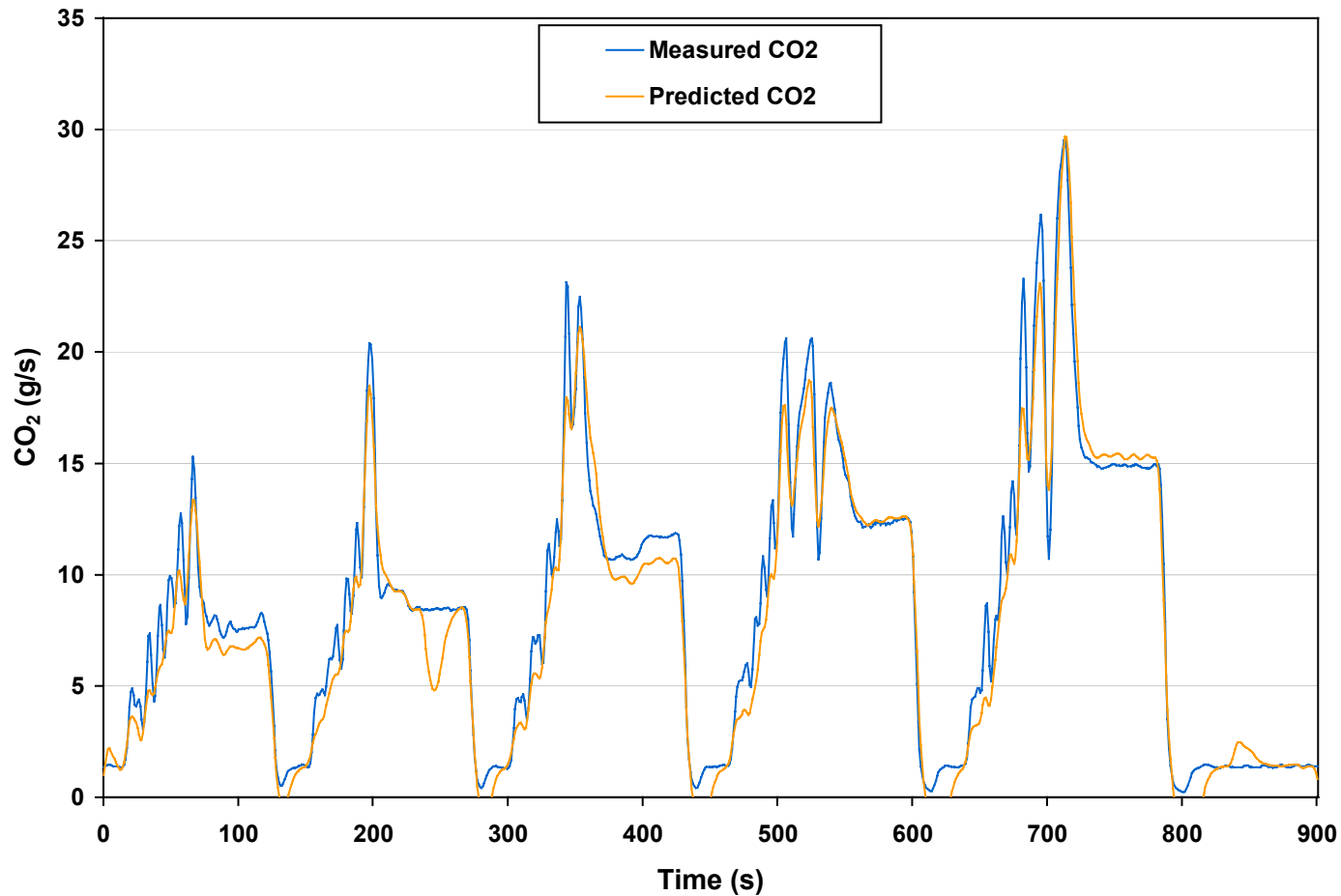
CO$_2$ emission results from the conventional vehicle (correlation)
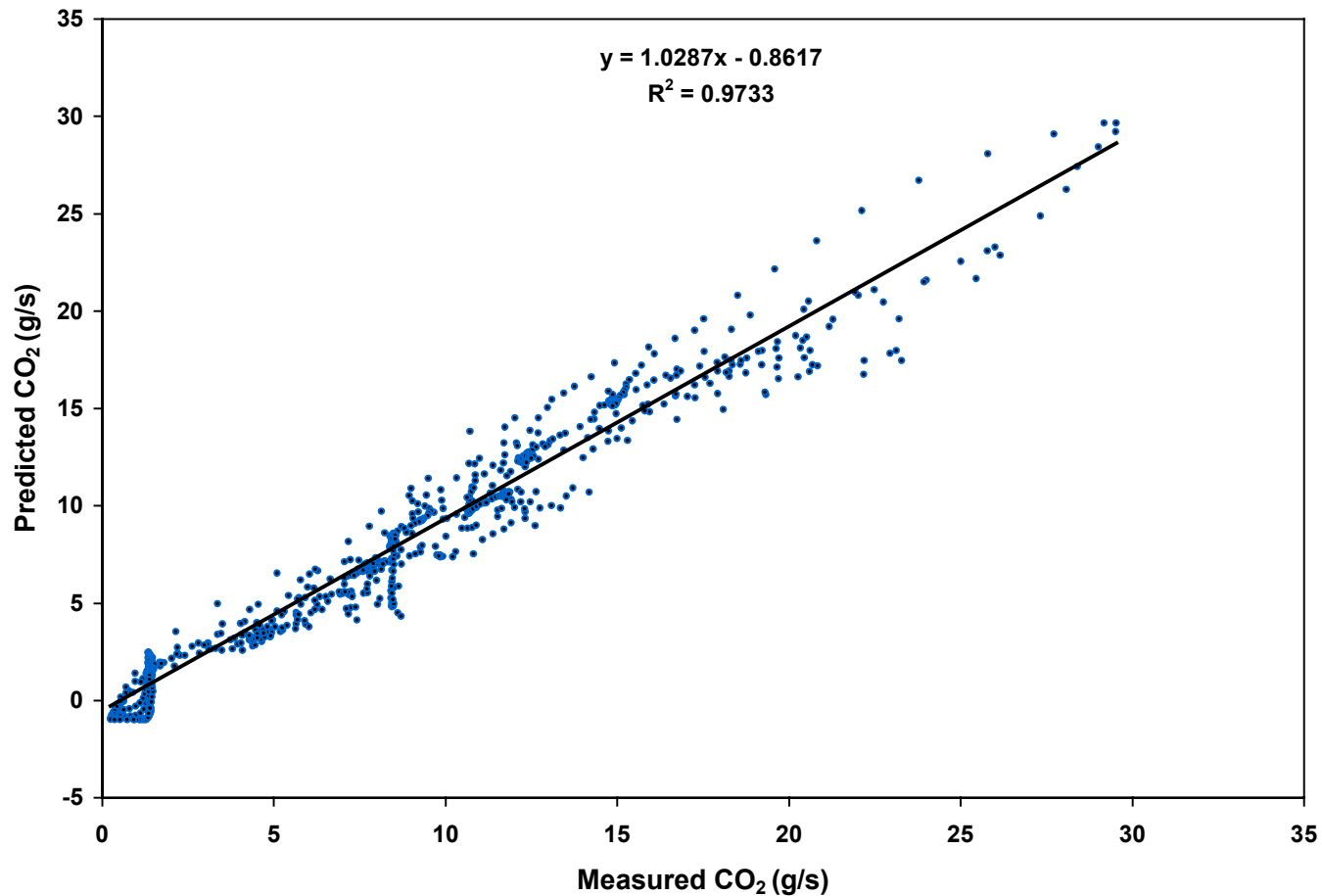
NOx emission results from the conventional vehicle
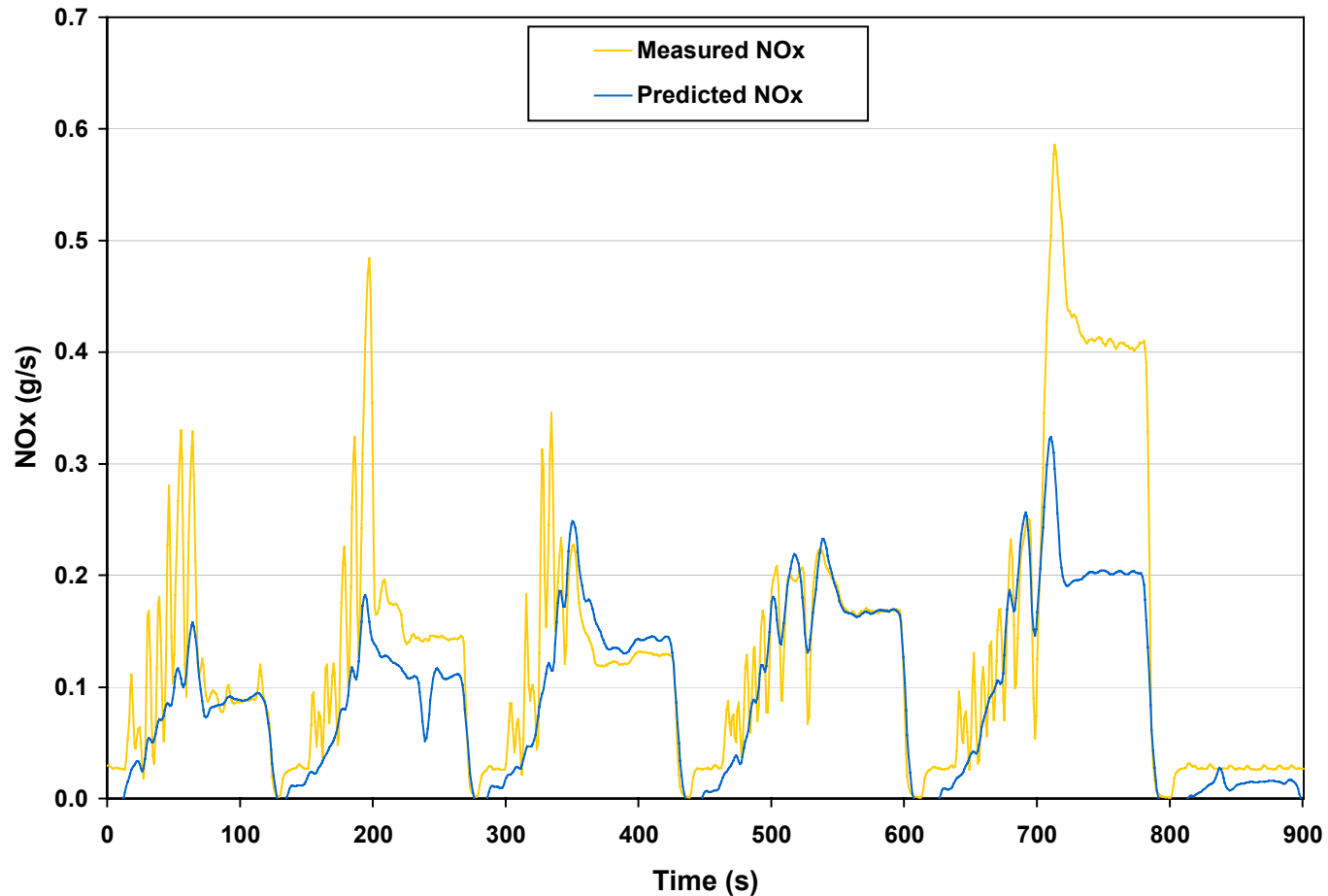
NOx emission results from the conventional vehicle (correlation)
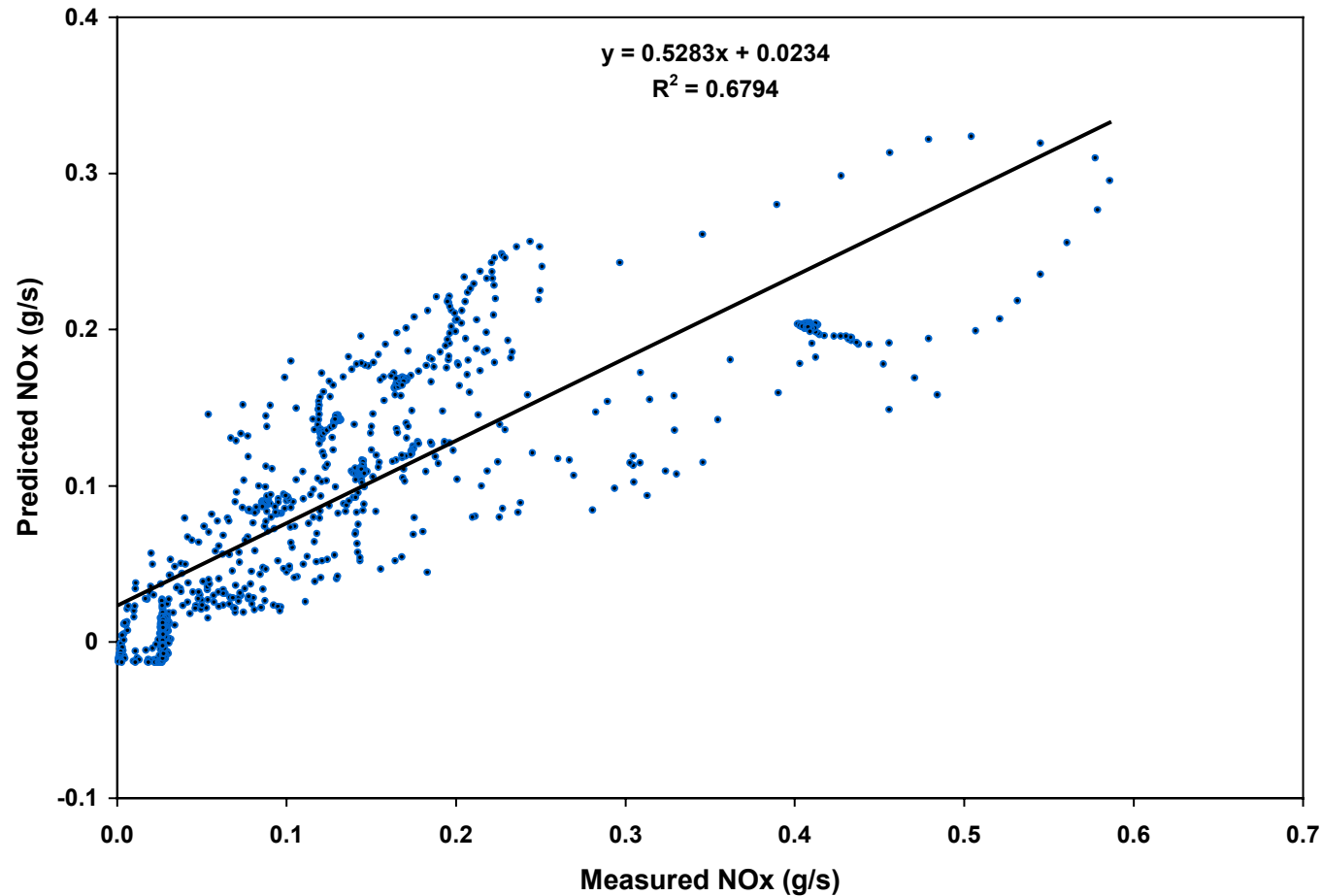
CO$_2$ emission results from the hybrid electric vehicle
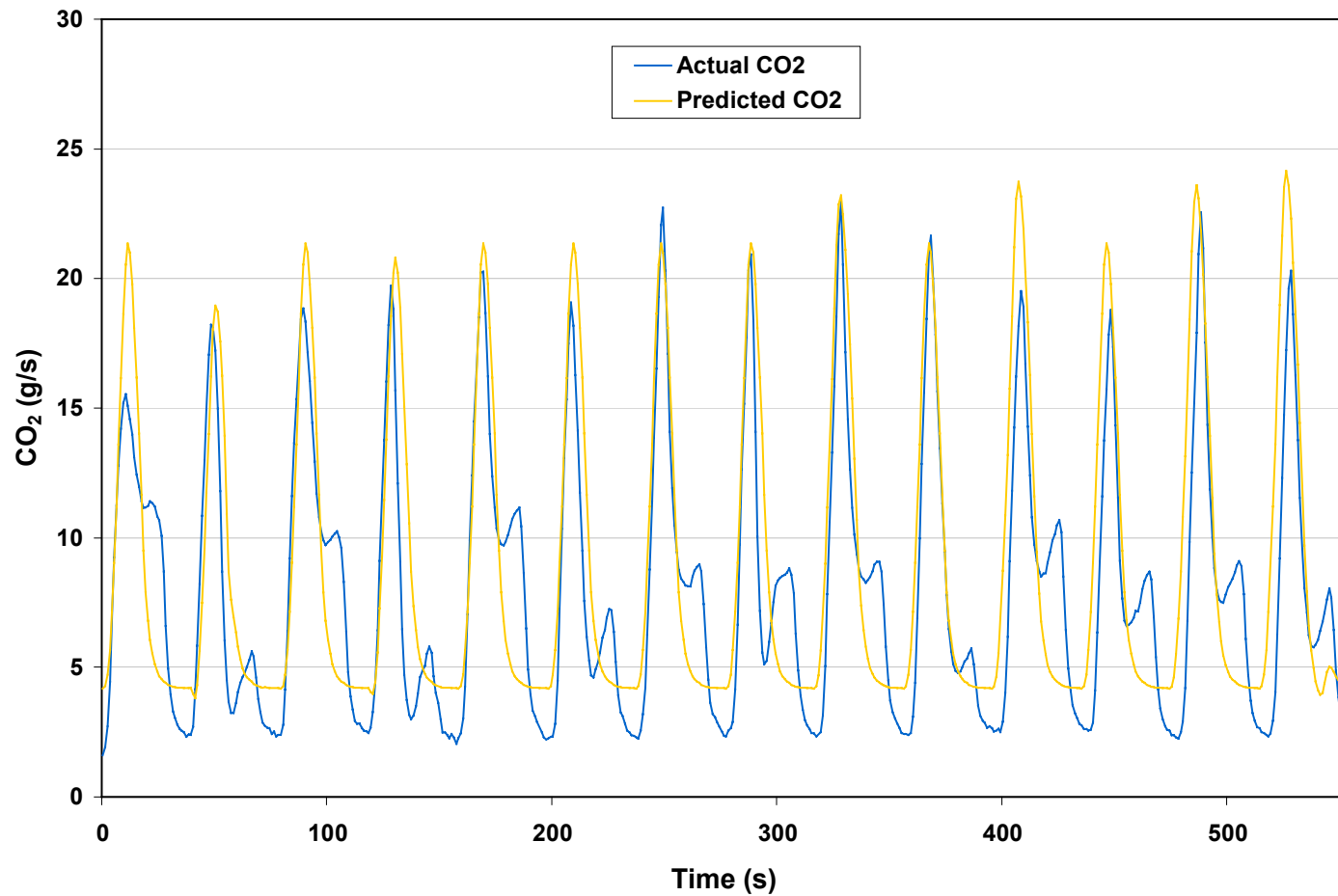
CO$_2$ results from the hybrid electric vehicle (correlation)
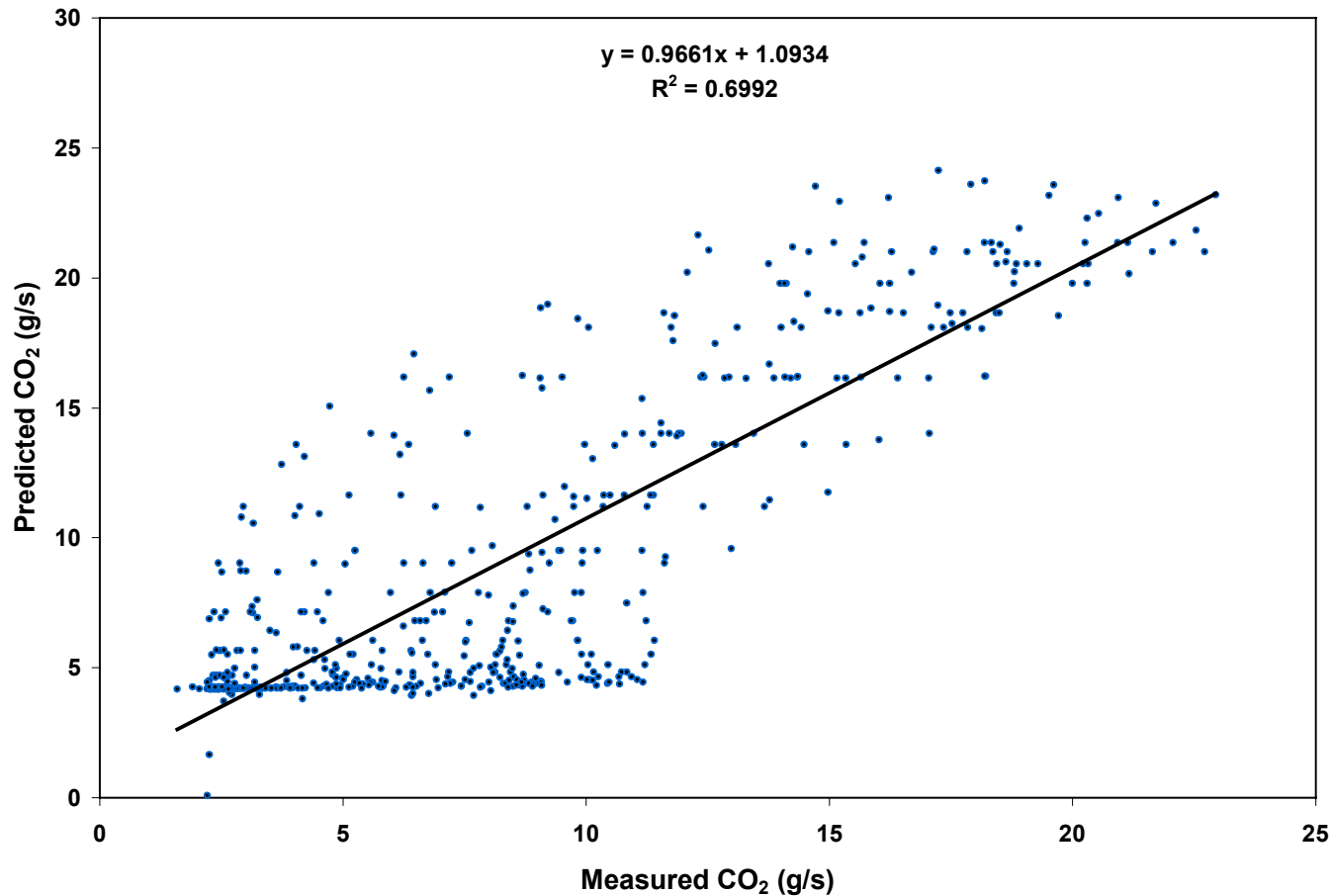
NOx results from the hybrid electric vehicle

NOx results from the hybrid electric vehicle (correlation)

y = 1.219x - 0.0113
$R^2 = 0.5727$

Predicted NOx (g/s)

Measured NOx (g/s)
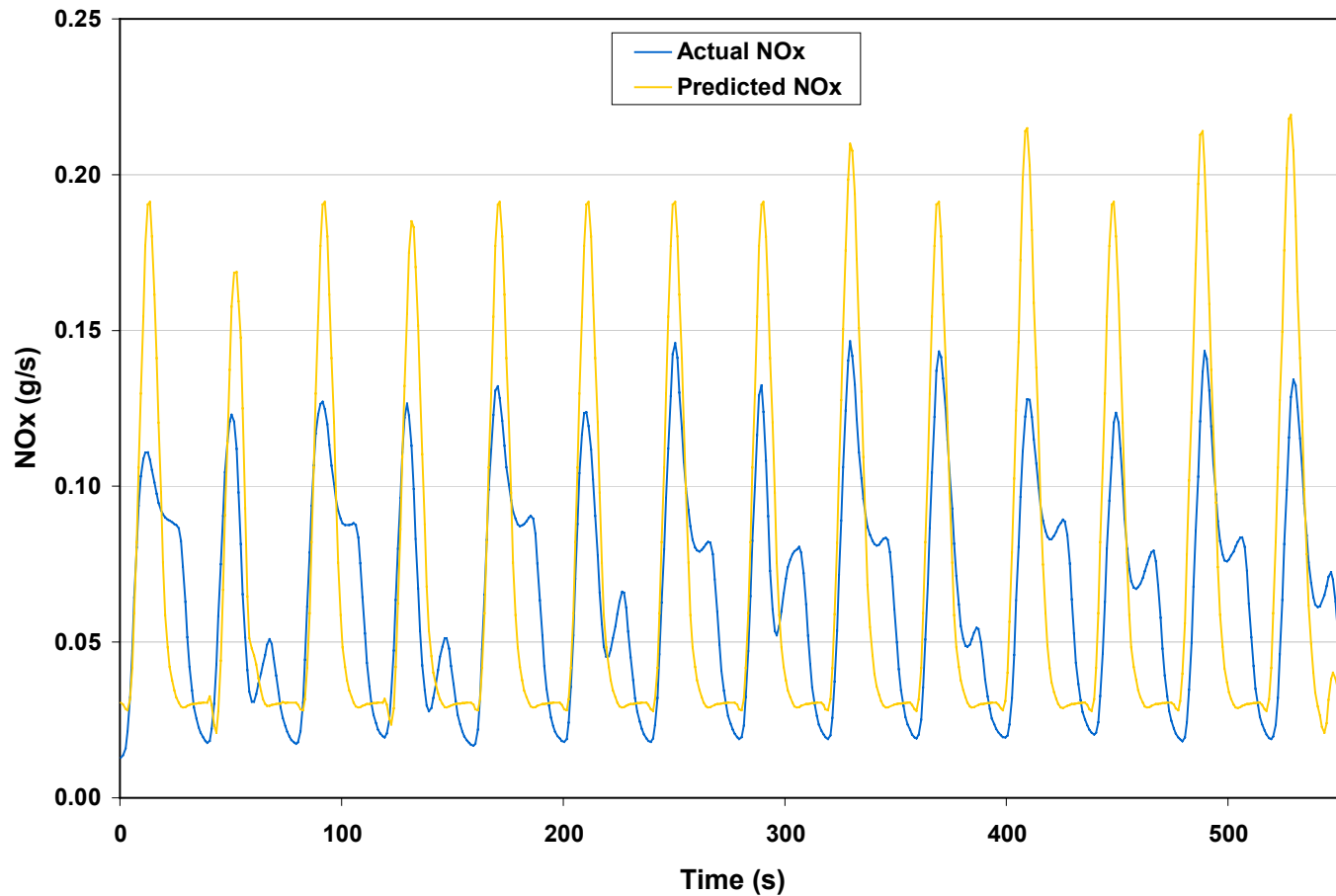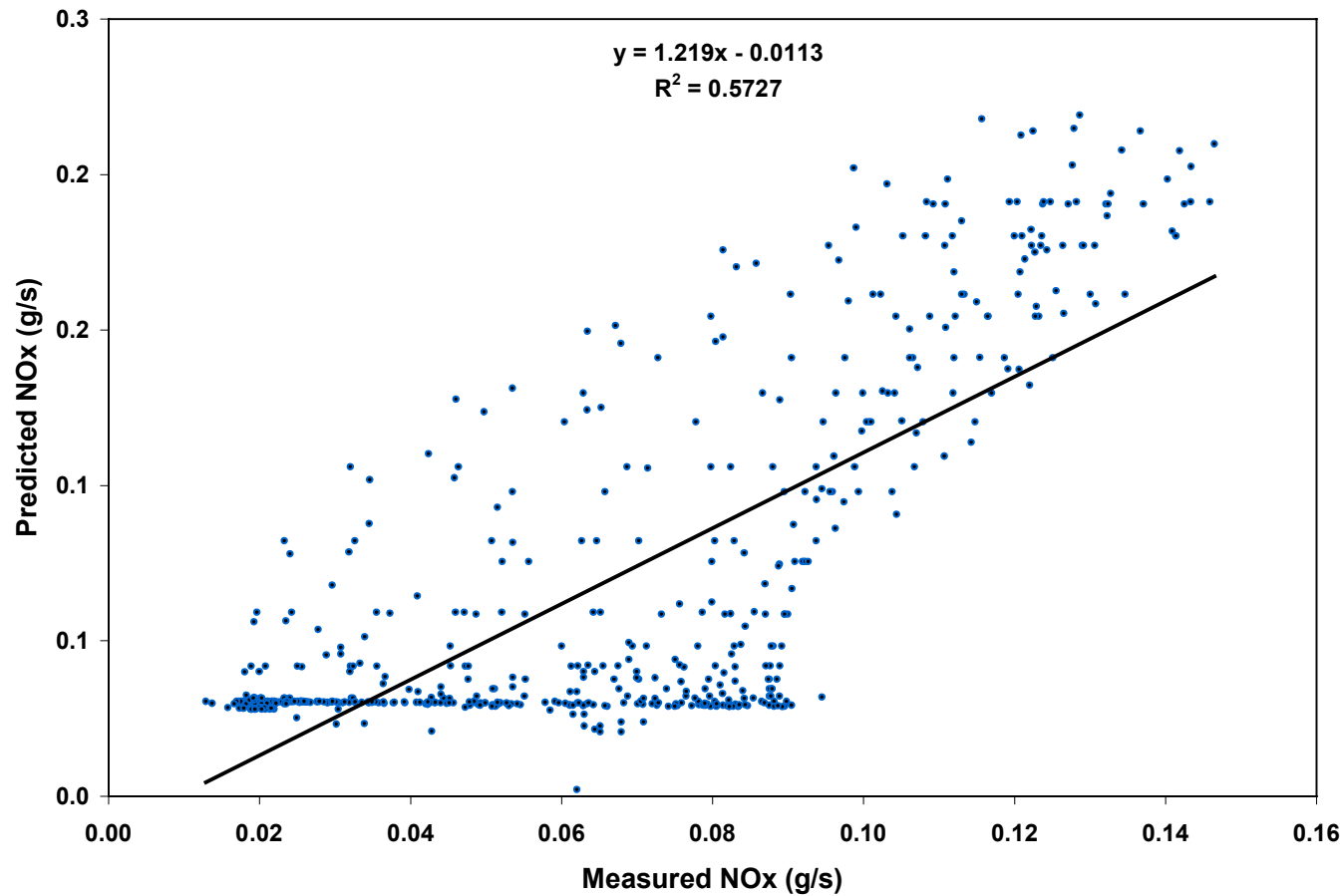
Summary

- Emission data from engine test
- Train artificial neural network
- Engine speed and torque from ADVISOR
- Predict emissions using ANN
- Emission data from chassis dynamometer test
- Compare predicted and measured results

Conclusions

- Artificial Neural Network / ADVISOR
  - Ability to handle transient engine operations
  - Great prediction tool for emissions
  - Excellent correlation with vehicle test

  - Control algorithm must be known
  - Off-Cycle NOx

Future work

- Apply extended back propagation method
- Develop emission models for particulate matter
- Develop emission models for different engines
- Further validation

Acknowledgement

- Michael O'Keefe
- Hybrid Electric Vehicle Work Group at WVU

Development of Transient Prius Engine Model Based Upon Neural Networks

Mike Duoba, Don Gray, Toma Hentea, and Mike Jakov

Argonne National Laboratory

DOE Vehicle Systems User Conference, August 28-29, 2001

Argonne National Laboratory
Transportation Technology R&D Center

Outline

- Need for Transient Engine Modeling

- Introduction to Neural Networks?

- Structure of Model

- Development Process

  - Measurement Approach

  - Pre-Processing

  - Validation Process

- Validation Results

- Conclusion and Future Work

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Needs For Transient Engine Modeling

- Transients are very important to emissions production

- Emissions modeling with map data have limited usefulness

- **National Research Council PNGV Review '99** *"The PNGV systems-analysis team should attempt to develop and validate vehicle emissions models of sufficient sophistication to provide useful predictions of the emissions potential for a variety of engine[s] (CIDI & SIDI).."*

- ANL staff have unique capabilities in Neural Network development methods (not off-the-shelf tools)

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Introduction to Engine Modeling with Neural Networks

The Neural Network Approach to Engine Modeling Utilizes

- Pre-processing modules which

    – Include time history

    – Have input parameter interrelations

- Neural Network based modules which

    – Provide model dynamics (inertia effects)

    – Characterize non-linear responses

    – Needs no underlying empirical equations

    – Is entirely data driven

Which When Linked Together Form A Complete Model

Neural Network Structure

Input
Layer
Neurons

Hidden
Layer
Neurons

Output
Layer
Neurons

Input
Variables

Predicted
Output
Variables

Weighted
Interconnections

Weighted
Interconnections
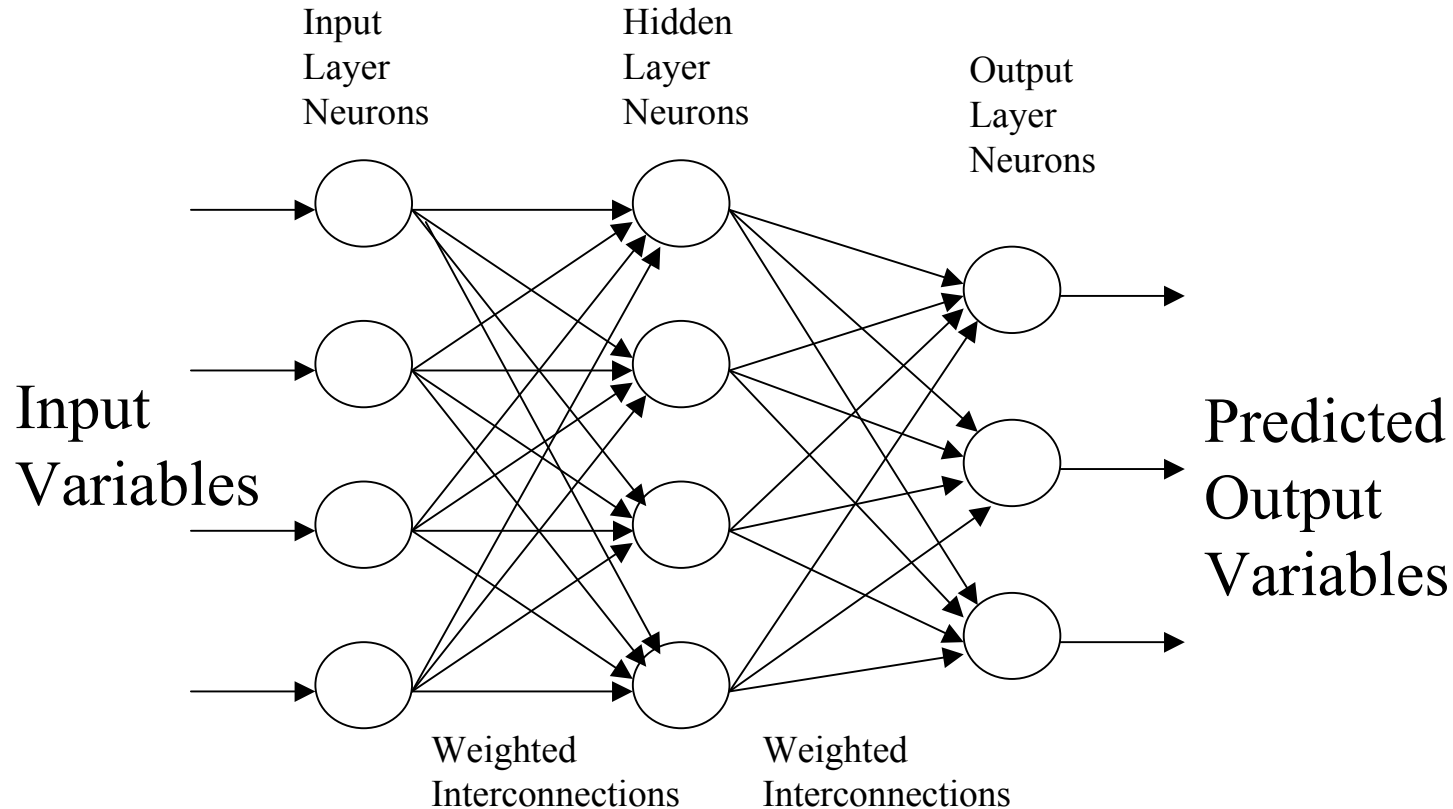
Example Neural Network Structure

The Basic Structure of Engine Model
(forward or backward compatible)

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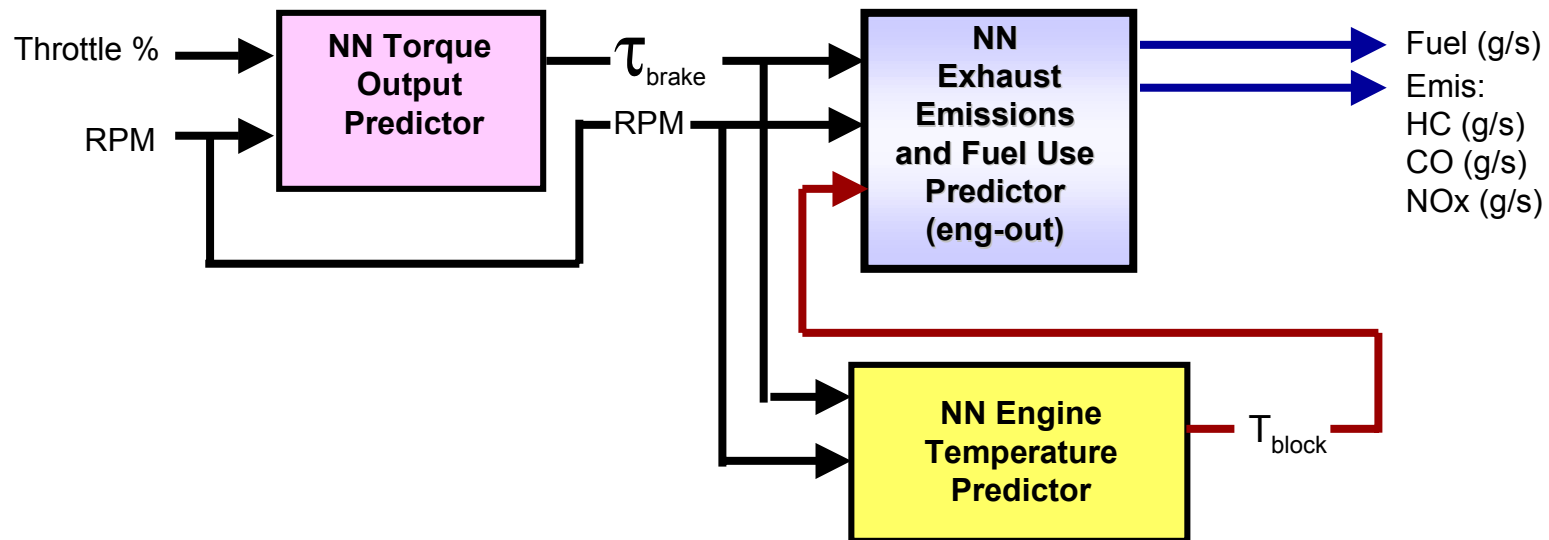
Direct Model Was Found To Be More Accurate
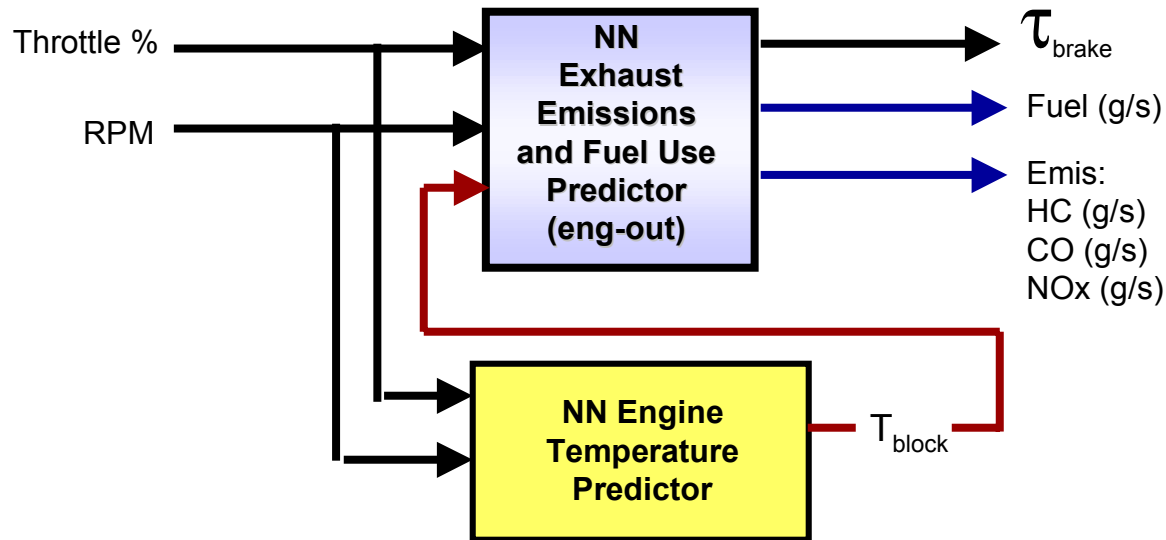
Interior Structure of Modules – Torque Predictor

Input Variables

Neural Network Torque Predictor Module

Output Variable

Throttle
Speed
Block Temperature
Fueling Command

Data Preprocessing

Neural Network

Engine Output Power

Development Process

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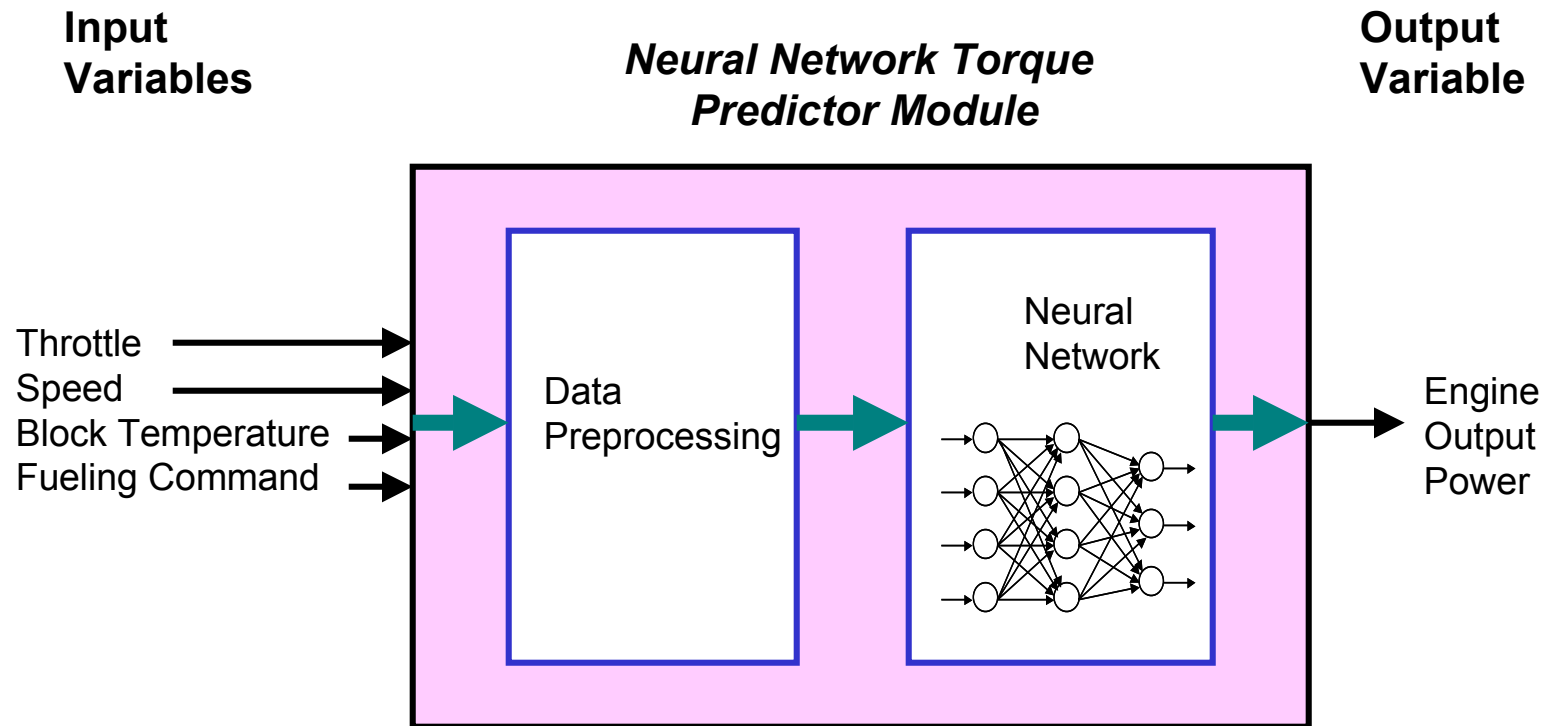
Japan Prius Test Data Collection

- Prius engine is first HEV-optimized OEM engine
- Transient engine data required: torque, RPM, fuel rate, emissions, temperature
- Engine cannot be tested outside of vehicle, ANL developed in-situ engine test method – *fidelity of dynamometer cell*
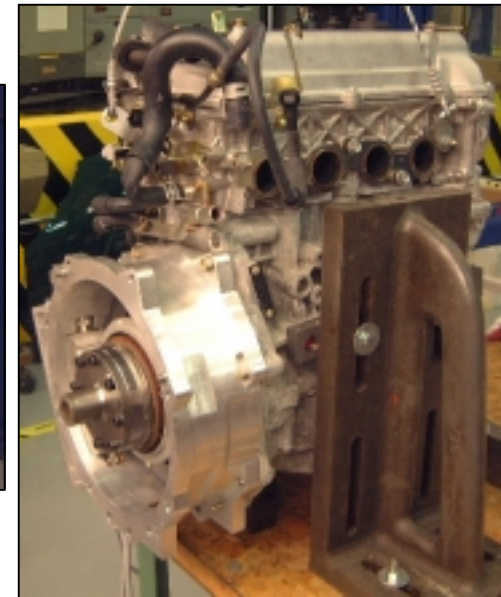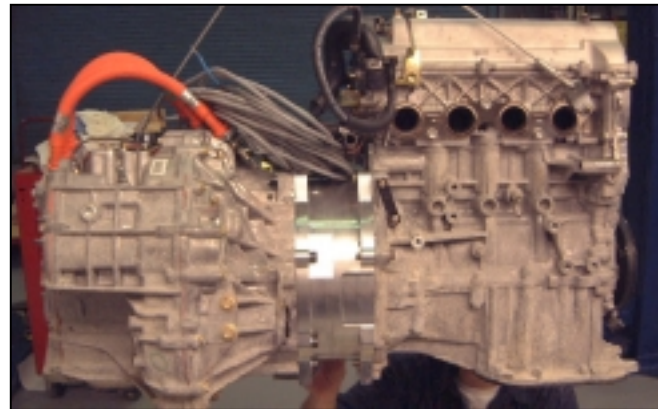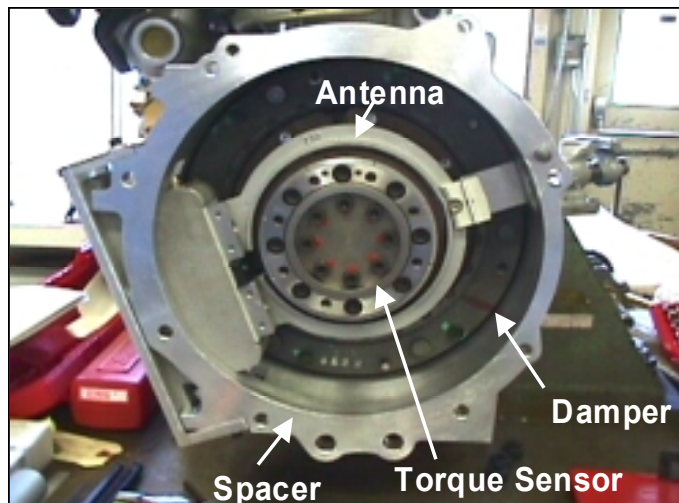
Prius 1Hz Neural Network Training and Validation

- Nine Cycles Used for Training

  -Cold Highway, UDDS, and Transient

  -Hot Highway, UDDS, 10-15, US06, and Transient

  -Warm NYCC

- Three Cycles used for Validation

  -Hot Highway

  -Cold FTP

  -Warm ECE

ANL Custom Neural Network Environment Required

Custom Network Benefits -Not found in generic software packages:

- Data preprocessing tools specifically generated for <u>Engine Modeling</u>.

- Custom 'Training' algorithms are incorporated to create a high precision Neural Network Model, in addition to faster Model generation.

- Potential for fully automatic Model generation of the entire system.

- Seamless environment from <u>data files</u> to a <u>completed Model</u>.

Standard NN Software Package Shortcomings:

- Neural Network packages do not create Neural Systems - Only individual Neural Networks

- Canned software is cumbersome to manipulate, and inflexible in operation.

Careful Pre-Processing Of Data Is Critical

- Careful manipulation of data provides input to NN sub-module

- Time history derivatives and integrals are generated

- Calculated input parameters are calculated (eg. power)

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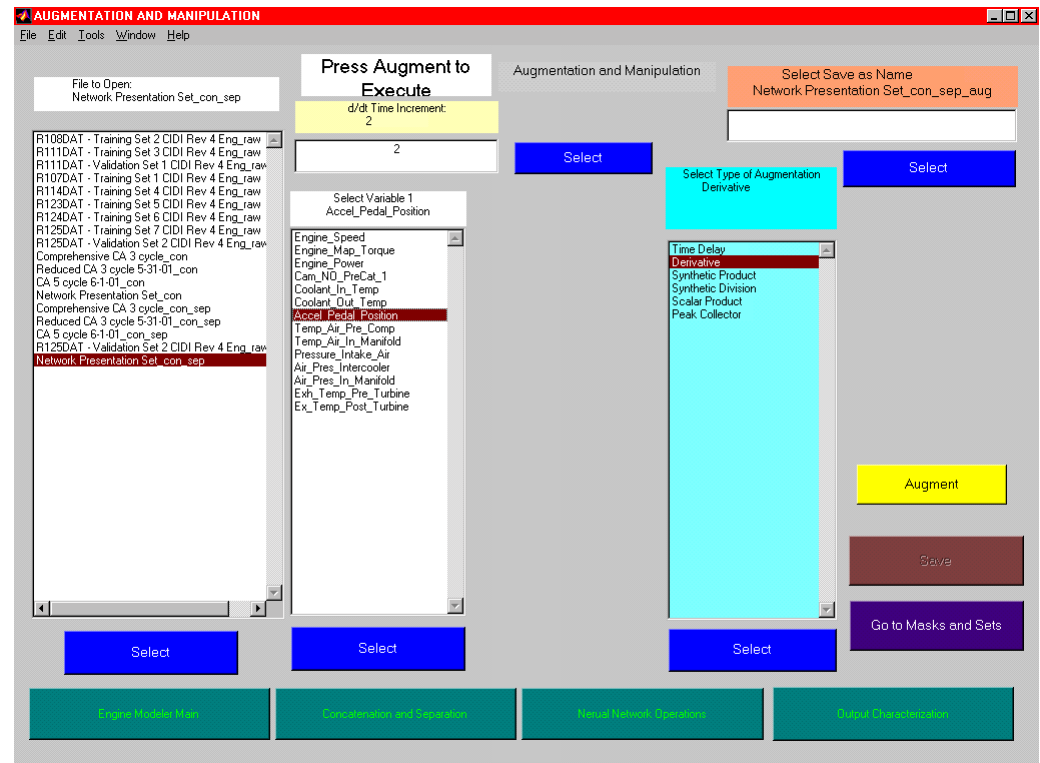
Training Process

- The Pre-Processed data file variables are categorized and defined into two groups:

    - Input Variables

    - Output Variable(s)

- Finally, the Network is exposed to the data, and trained to predict the Target Output(s).

- Validation data is recorded data not originally exposed to the network

- Validation input data is pre-processed then run through network

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Validation Process

Validation Process

- Validation data is aquired data not originally exposed to the network

- Validation input data is pre-processed then run through network

- Network parameters are changed and iterations are run to provide the best prediction

Optimization of NN Requires Error Analysis
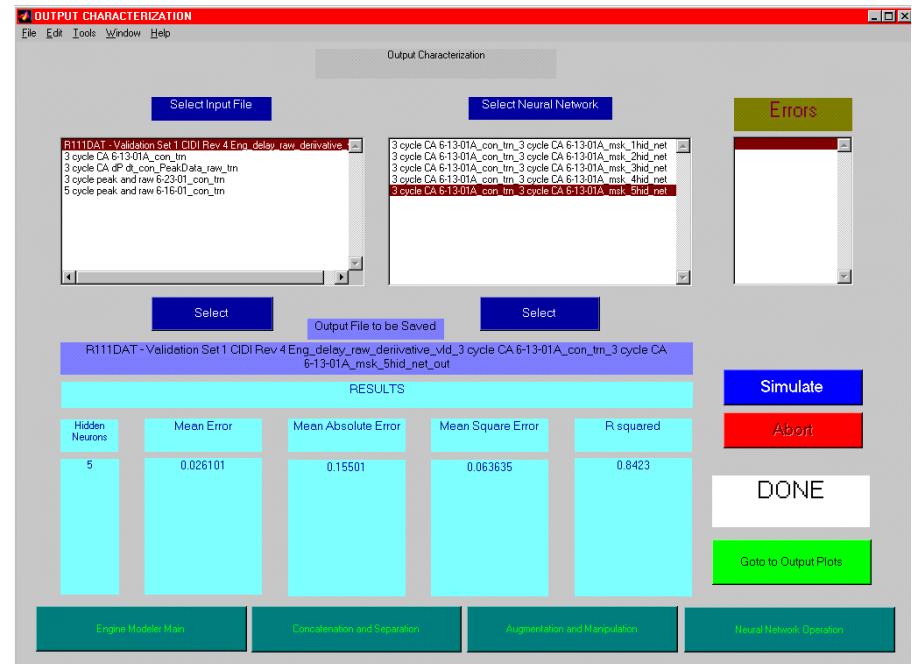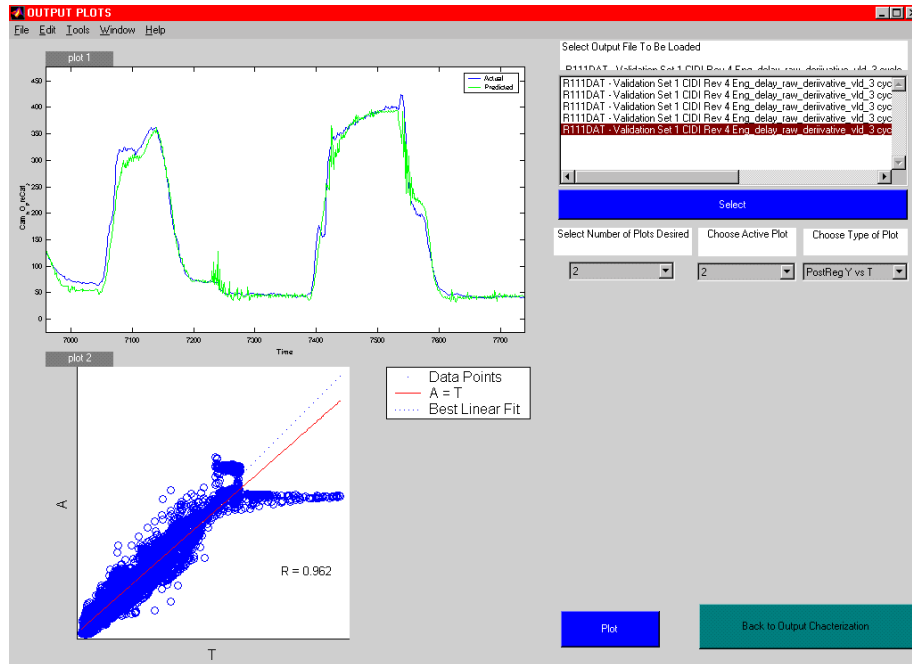
- Human interaction is required to find best solution
- Correlation constants, error calculation, and graphical characterization all contribute to optimization
- "Cost" functions are used to trade-off types of error

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Validation Results

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Validation Results:
Power Module Outputs

power9by12$_8$ power prediction for hot hwy

HC prediction for ECE

Transient engine shut-down spikes are captured
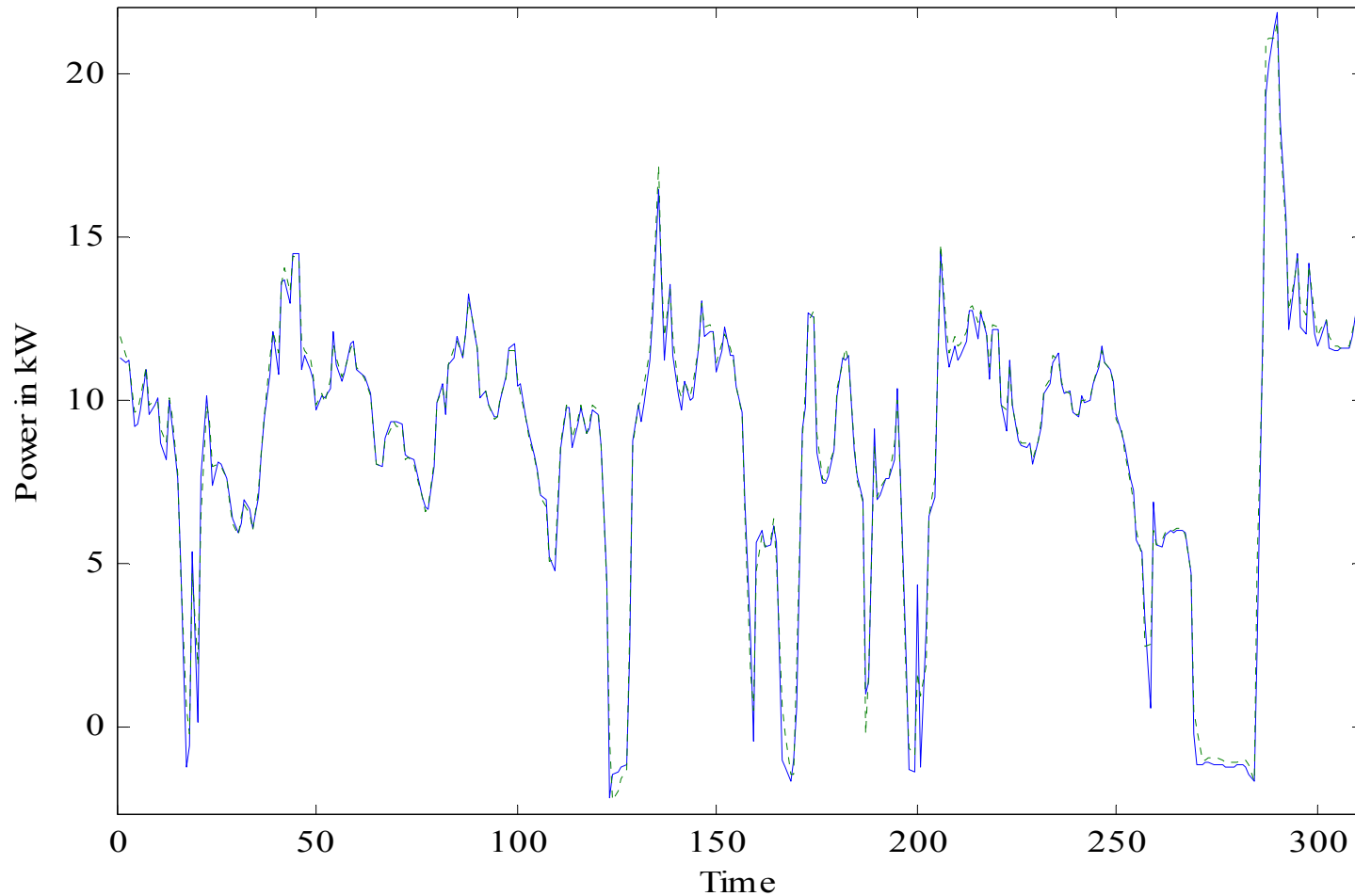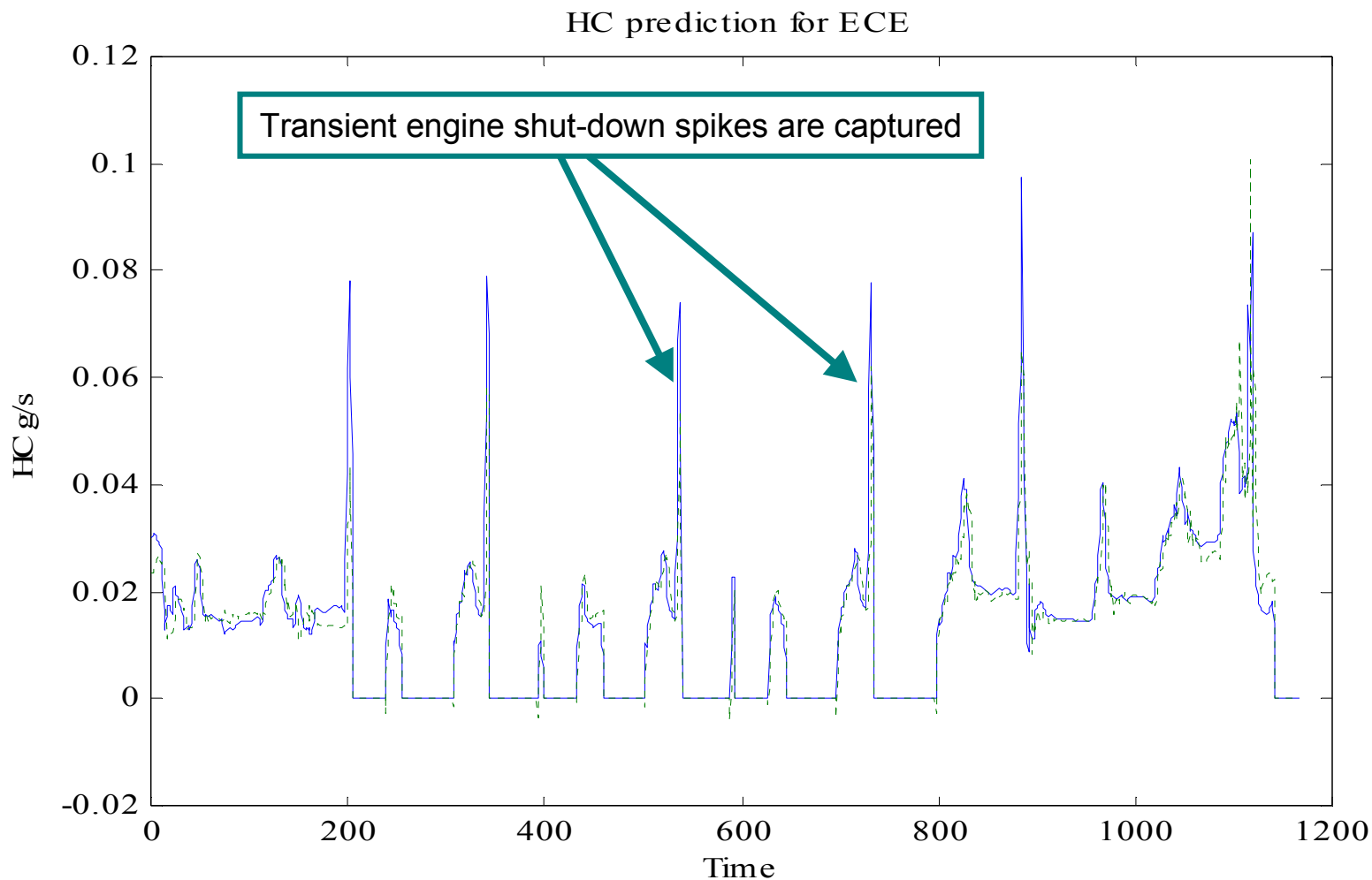
Sufficient Training Data Needed For Validation

power9by12$_8$ power prediction for cold FTP

Initial cold-start not captured

Later (warmer) data more successful
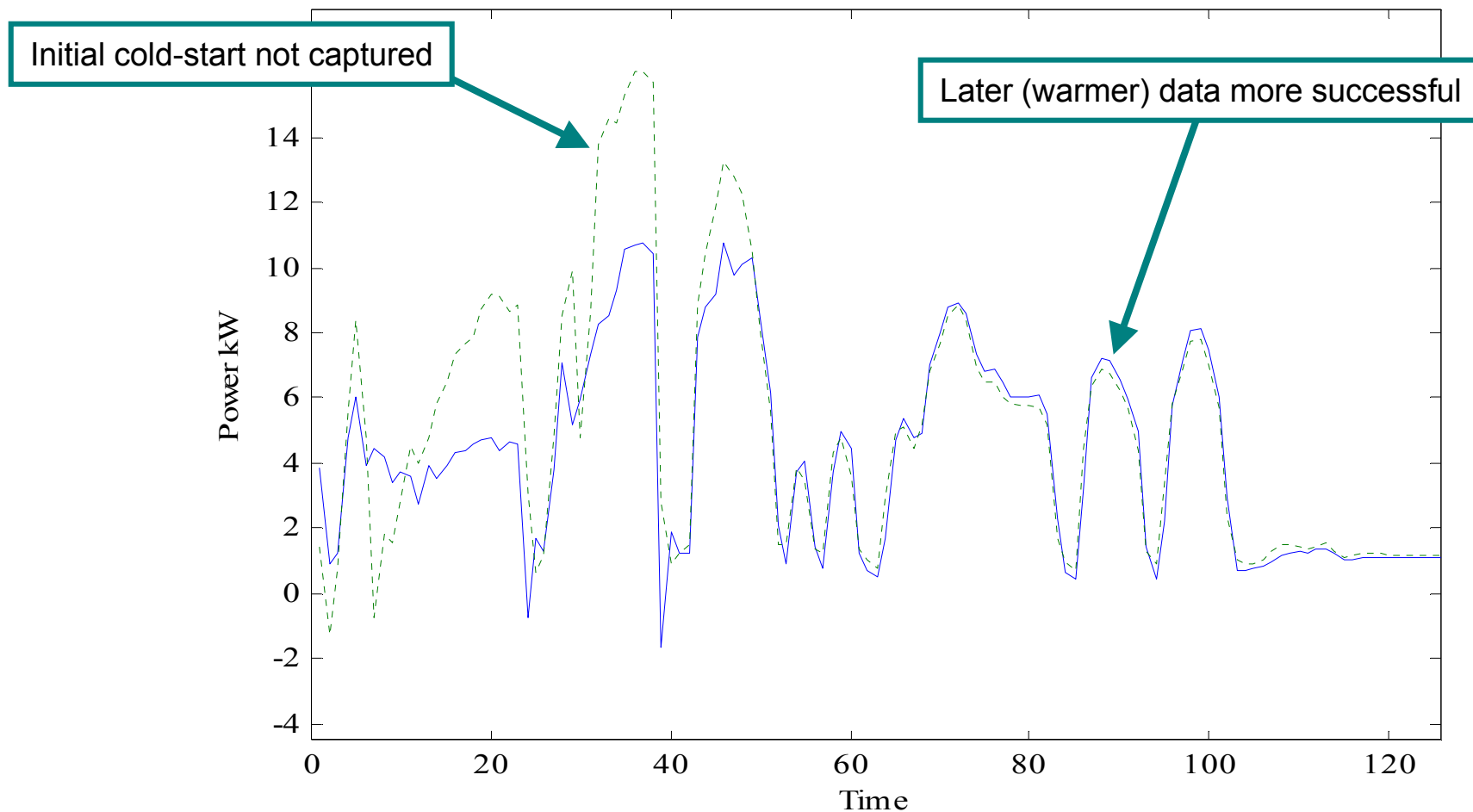
HC Output Plots

HC prediction for Cold FTP
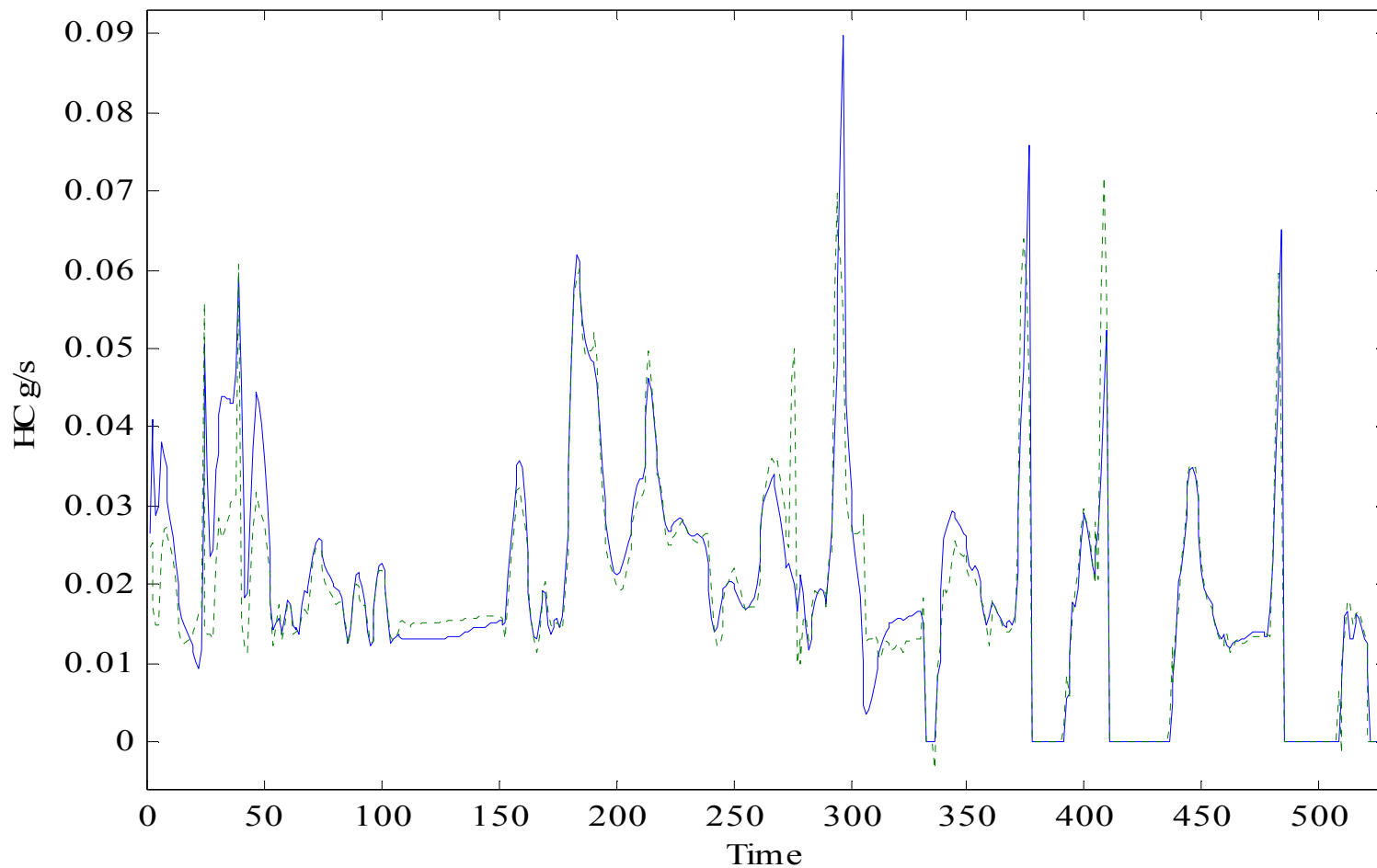
Validation Results:
CO Emissions Prediction

CO prediction Cold FTP

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Transportation Technology R&D Center
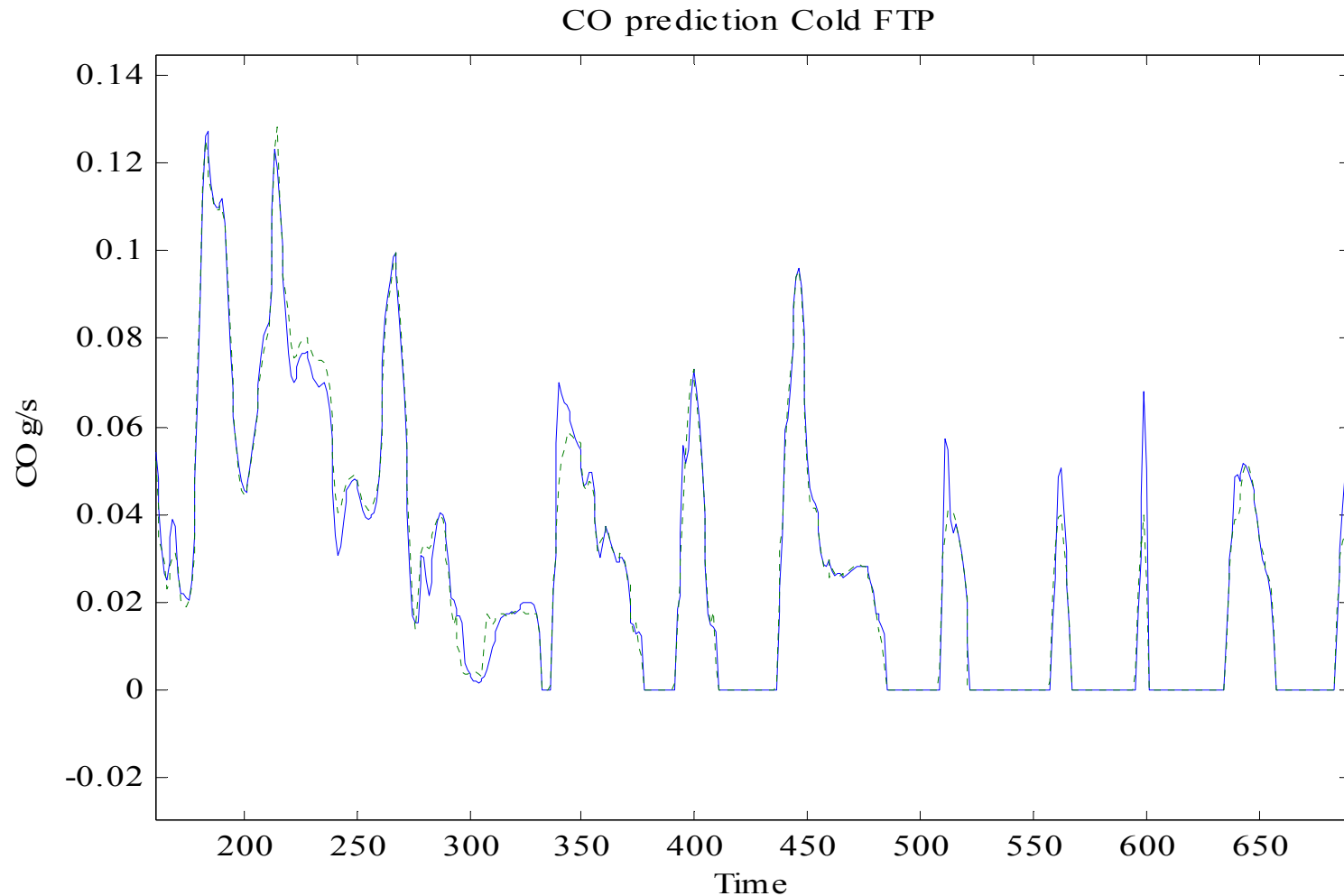
Results and Future Work

- Models based on limited 1Hz data were produced with compelling results

- Results show limited training data will reduce predictive capability (initial cold-start shown)

- Work continues to produce models from ANL data at 10Hz

- Other investigations will show
  - How much data is needed for valid results
  - To what extent might we need to weight data that is of more interest

- Also focus on CIDI engines
  - Torque predictor more useful (turbo-limited slew rate)
  - Using ANL-developed 10Hz PM measurements (Laser Induced Incandescence [LII])
  - Off-line simulation of control strategies that can simultaneously reduce transient NO and PM in HEV configuration

Keynote Address

The Future of Green Vehicles: How We Get There From Here

Larry Oswald,
Vice President Hybrid Electric Vehicle Platform Engineering,
DaimlerChrysler Corporation

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Automotive Technology Is Entering an Era of Major Change

- IC engines have been evolving for over 100 years.
- Today's engines represent a high degree of efficiency and environmental controls.
  - 98-99 percent of regulated emissions are now removed from exhaust.
  - Thermal efficiency is approaching theoretical maximum.
- New emission standards take effect beginning in 2004 require even lower emissions
- Continued debate about the environmental impact of the automobile.

What Is the Industry's Response?

- **The auto industry is engaged in unprecedented development of advanced technology.**
  - **Further improvements in the IC engine, using techniques such as cylinder deactivation, improved transmissions, and improved combustion processes. Fuel efficiency improvements will be incremental, but gains of 15-20 percent could be achieved.**
  - **Electric vehicles, such as the Neighborhood Electric Vehicle (DaimlerChrysler's GEM) and City Electric Vehicles, are beginning to sell.**
  - **Hybrids, which offer the greatest potential for improved fuel efficiency in the mid-term (5-15 years into the future), are entering the market. Hybrids offer 20-50 percent improvements in fuel efficiency with lower emissions.**
  - **Fuel cells could result in zero emission vehicles with <u>twice</u> the fuel efficiency starting in 10-15 years.**
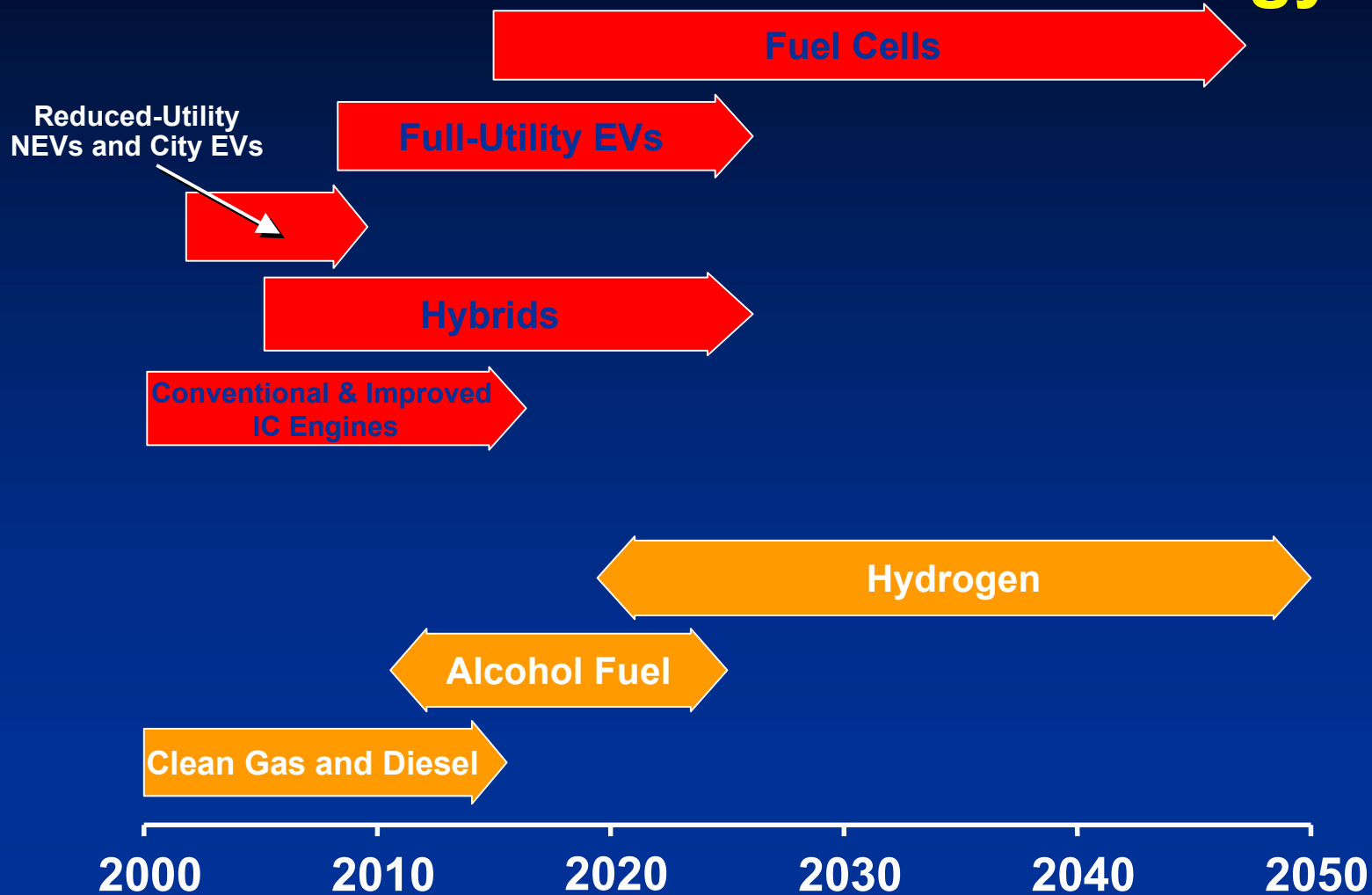
Why Neighborhood Electric Vehicles?

- **Replace IC vehicles on most-polluting short trips with multiple cold starts.**

- **Are becoming a transportation niche.**

- **Street-legal in 38 states; classified as zero emission.**

- **DaimlerChrysler purchased Global Electric Motorcars, November 2000.**

- **GEM will produce more than 20,000 units in 2001 and 2002.**

Why Hybrid Electric Vehicles?

- **Hybrids offer the greatest potential for improved fuel efficiency and performance in the mid-term.**
- **Hybrids incorporate technology that we know a lot about and can move into production quickly.**
  - **Electric motors.**
  - **Internal combustion engines.**
  - **Batteries.**
- **Addresses carbon dioxide emissions through improved fuel efficiency.**
- **Reduced emissions such as hydrocarbons and nitrogen oxides through use of smaller internal combustion engines.**
- **Offers added customer features and benefits.**

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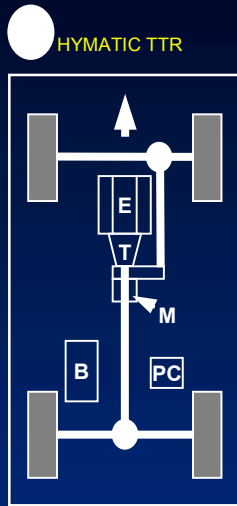
HYMATIC TTR
E-CLASS PROTOTYPE

DURANGO TTR
DURANGO PROTOTYPE

WHEELMOTOR TTR

ELECTRIC FRONT DRIVESHAFT TTR
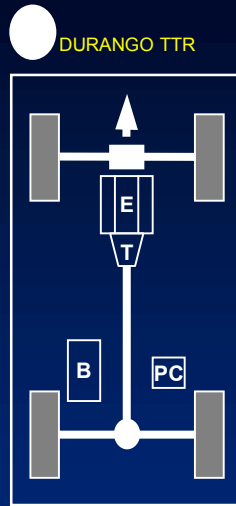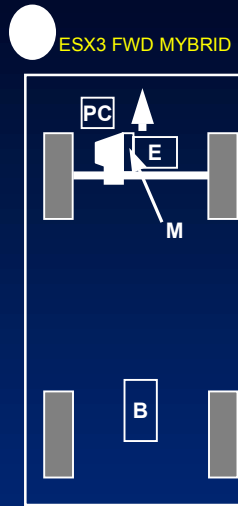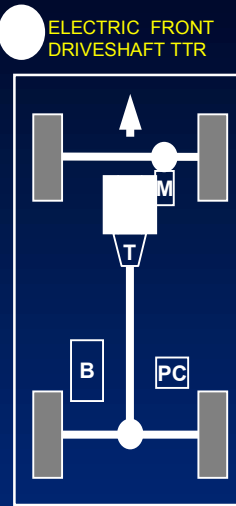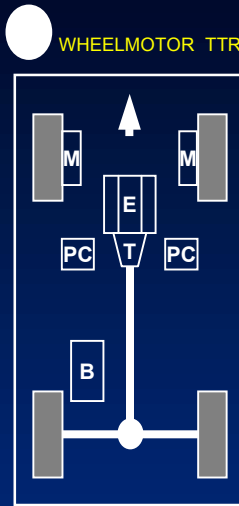
ESX3 FWD MYBRID
- FORD PRODIGY
- HONDA INSIGHT
GM PRECEPT
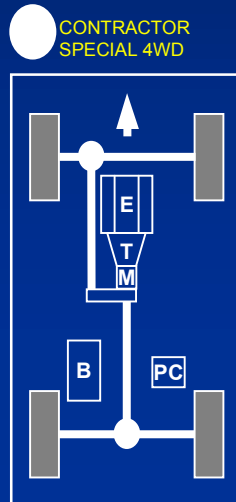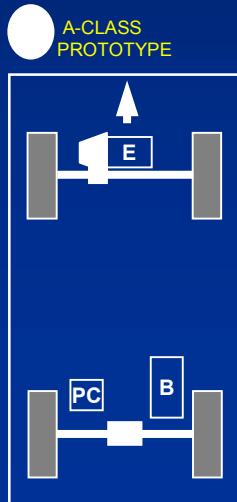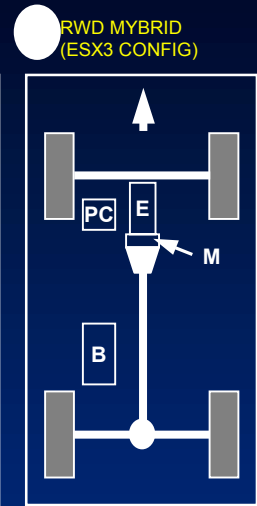
RWD MYBRID (ESX3 CONFIG)

A-CLASS PROTOTYPE

CONTRACTOR SPECIAL 4WD
GM LIGHT TRUCK FOR ELETRIC POWER TAKE-OFF, ONLY
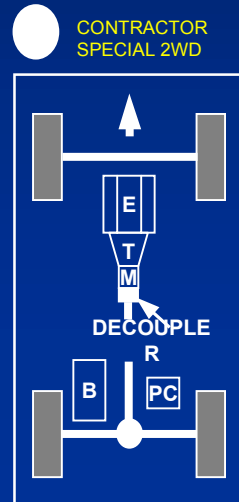
CONTRACTOR SPECIAL 2WD
GM LIGHT TRUCK FOR ELETRIC POWER TAKE-OFF, ONLY

TORQUE CONV. MOTOR HYBRID

POWER-SPLIT FWD
TOYOTA PRIUS FORD ESCAPE

POWER-SPLIT RWD

DAIMLERCHRYSLER
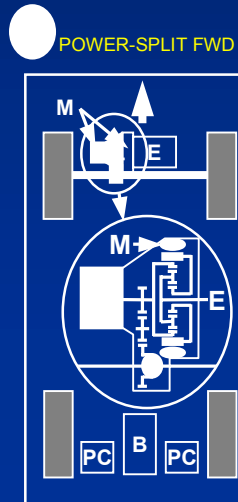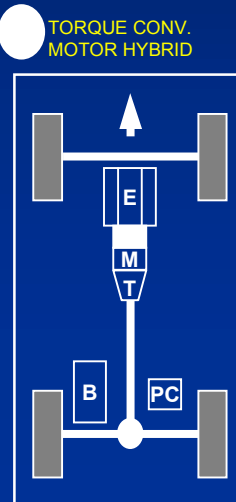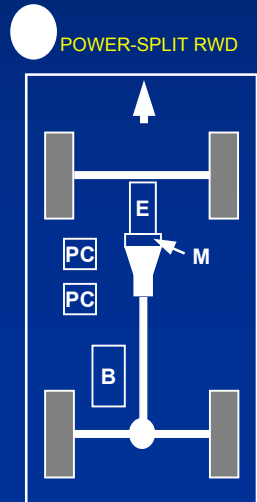
HEV's

Toyota Prius

Ford Escape 2004

Ford Explorer 2005

Honda Insight

GM Paradigm 2004
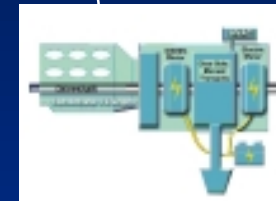
DC Ram "Contractor Special" 2005

GM Silverado 2004

DC Durango 2004

- 15 - 40% Improvement in fuel economy

- $3000+ cost increase

- Fuel savings does not offset the hardware cost

- Tax incentives are important to help start sales

Chrysler Hybrid Concept SUV's

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Citadel   1998

PowerBox 1999

Jeep Commander 2   2000

DaimlerChrysler's Hybrid Strategy

- **Maximize the real-world customer benefits of hybrid technology by offering more features.**

- **Increase the potential for greater sales by applying HEV technology in best selling, high volume vehicles.**

- **Apply hybrid technology to vehicles with relatively lower mpg so that each percentage gain in fuel efficiency yields the greatest savings in gallons of fuel consumed.**

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Fuel Economy Arithmetic

• **Fleet Mix**	**Case 1**	**Case 2**	**Case 3**
• **Hi Fuel Econ**	45 mpg	49.5 mpg	45 mpg
• **Lo Fuel Econ**	15 mpg	15 mpg	16.5 mpg
• **Net Fuel Econ**	22.5 mpg	23.0 mpg	24.1 mpg
• **Gal./Veh. Save**	--	242	727

– 12000 mile/Vehicle/year

DaimlerChrysler's Hybrid Strategy (cont'd)

- **Reduce emissions through use of smaller internal combustion engines.**

- **Work for customer incentives so hybrid technology is cost effective for the customer.**

  – **Durango hybrid - $3,000 price premium compared with conventional Durango.**

  – **RAM hybrid with Auxiliary Power - $5000 price premium compared with conventional RAM**

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DaimlerChrysler will begin marketing fuel efficient hybrid vehicles in 2003

- Our first hybrid vehicle will be the Dodge Durango SUV, using our patented Through-The-Road hybrid powertrain technology.

- We will follow that with the Dodge Ram Contractor Special in 2004.

Dodge Ram 'Contractor Special'
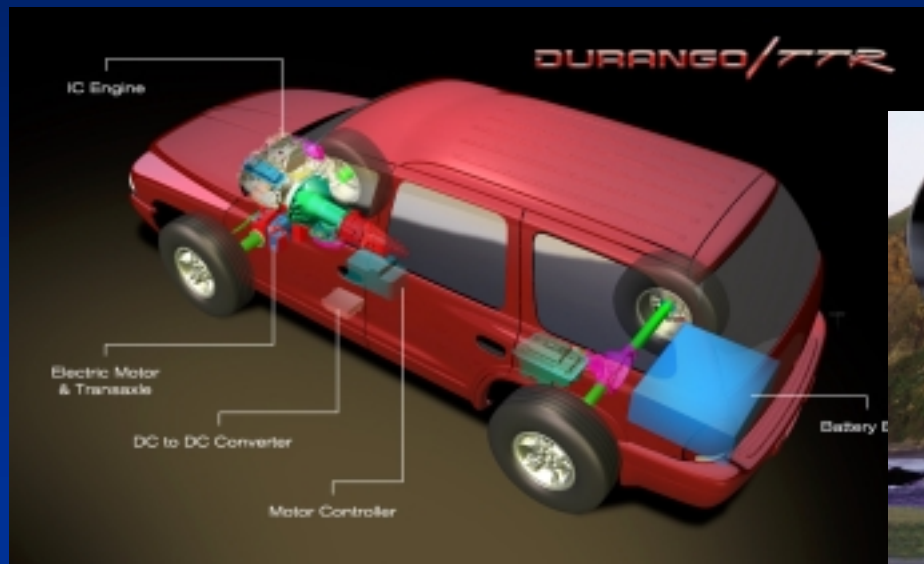
- **Production Targeted for CY'04**
- **15% Fuel Efficiency Improvement**
- **Generates 20 kW of 110V/220V Auxiliary Power**
- **Motor/Generator is Integral to Conventional Gasoline or Diesel Powertrains**
- **$5,000 Estimated Cost Premium**

- **Cleaner than a Conventional Pick-up Truck On-Road and Cleaner than Current Generator Technology Off the Road**

Ram "Contractor Special" Chassis
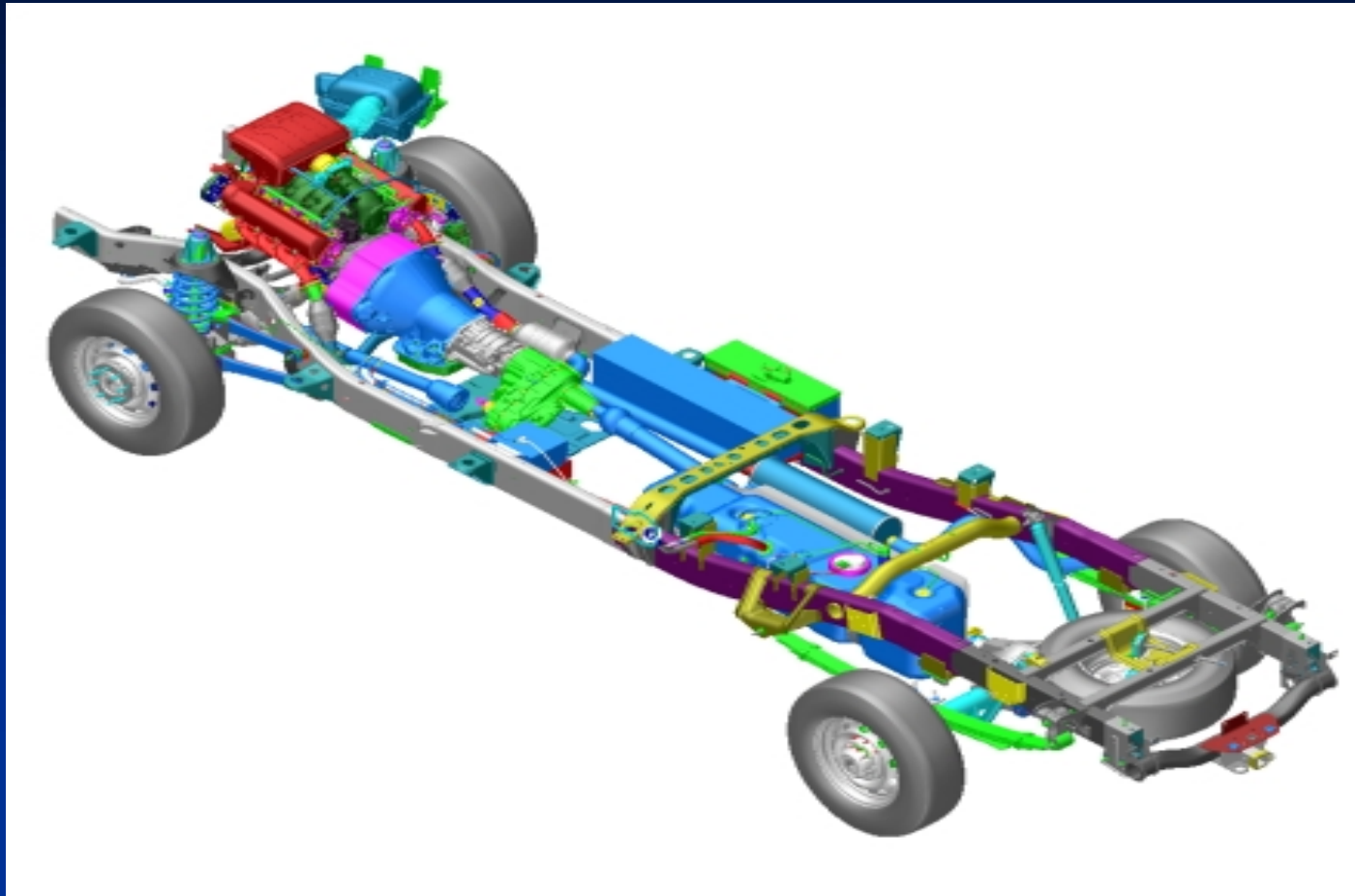
Dodge Ram COMBATT

Commercially Based Tactical Truck derived from the production Dodge Ram 2500 pick-up.

Enhanced mobility features

HEV Propulsion with Integrated Auxiliary Power
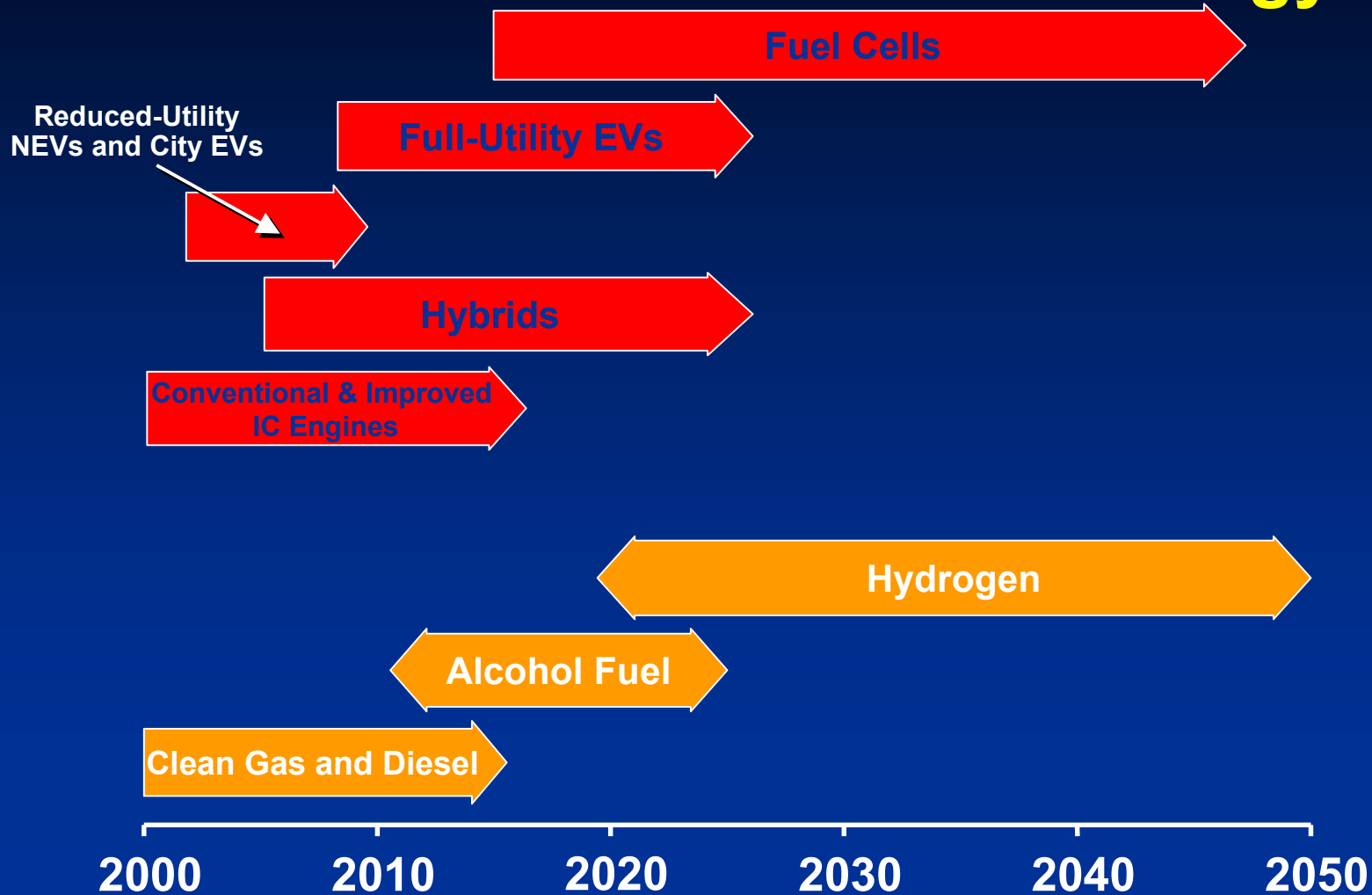
A Look at the Long-Term: Fuel Cells

- The relatively large size, complexity, high cost and establishing the optimum fuel infrastructure for fuel cells will keep the sales numbers small for at least 10 years.

Mercedes Benz Buses

NECAR 5

Commander 2

- In the transition, piston engine hybrids will co-exist with fuel cell hybrids.

Concluding Remarks

- Customer expectations and choice are driving forces in the automobile market; therefore, overall fleet fuel efficiency is largely dependent on customer product selection.

- Products that customers want must be created in light of societal, shareholder and regulatory demands.

- Advanced technologies are the only opportunity for improved fuel efficiency that is directly actionable by automakers.

Concluding Remarks (cont'd)

- Cooperation and support of Government is important to accelerate development of promising advanced technologies.
  - **Fuel quality improvements**
  - **Cooperative technology development programs, such as PNGV, 21st Century Truck Initiative, COMBATT, etc.**
  - **Hybrid and fuel cell customer tax incentives**
  - **Collaborative support of long range technology development including modeling and simulation tools**

HEV Simulation Model Needs List

- **Wide Ranging Component Library**
  - **Energy Converter**
    - **Advanced fuel and high efficiency Engines & Fuel Cells**
    - **Advanced Batteries, Motors, Inverters, CVTs, etc.**
- **Flexible Hybrid Configurations and Control Algorithms**
  - **Forward and Backward Models with various methods for motor assist.**
- **Tail-Pipe Emission Prediction (Cold & Warm)**

HEV Simulation Model Needs List (cont'd)

- **Performance, Fuel Economy, and Emission prediction including long term aging effects.**

- **Vehicle Stability and Dynamic Modeling incorporating multiple drive axles:**
  - **Traction control and split-mu surface braking**
  - **Yaw, Pitch and Roll**

- **Component and System Analysis for Reliability, Durability and Duty-Cycle for the life of the vehicle.**

- **NVH, Drivability and "Peppy-ness" rating or feedback for any particular control algorithm.**

HEV Simulation Model Needs List (cont'd)

- **Battery charge sustaining and balancing control algorithms**

- **Thermal modeling of battery and other electrical components**

- **System Optimization Tools**
  - **Optimal Component selection for given criteria**
  - **Trade-off Study (i.e., Performance and Fuel Economy)**
  - **Component Tolerance vs. System Sensitivity (Monte Carlo)**

HEV Simulation Model Needs List (cont'd)

- Interface to Rapid Prototype Tools
  - **Software Development Tools from dSpace, ETOS, xPC, etc.**

- *Stretch Goal:*

  - *Reverse Optimization Model: for given fuel economy, performance and vehicle mission targets, the model would provide the vehicle parameters such as CdA, Weight, Engine and Motor power, etc.*

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Software Applications

Implementation of Embedded C Software Within PSAT to Facilitate Hybrid Electric Vehicle Powertrain Control Strategy Development

Robert Schurhoff and Avernethy Francisco,
Hybrid Electric Vehicle Center, University of California, Davis

Presentation
Paper

Impact of Data Capture on Simulation Speed For Large Scale Models (ADVISOR/PSAT)

Swami Gopalswamy, Emmeskay Inc.

Implementation of Embedded C Software within PSAT to Facilitate Hybrid Electric Vehicle Powertrain Control Strategy Development

Rob Schurhoff

Vern Francisco

Hybrid Electric Vehicle Center
University of California at Davis

August 29, 2001
Joint Advisor/PSAT Conference
Southfield, Michigan

Hybrid Electric Vehicle Powertrain Control Overview

LEGEND
→ Mechanical Torque (red)
--▶ Control Command (green dashed)
→ Feedback (blue)

Driver · Controller · Vehicle · Engine · Clutch · Electric Motor · Transmission
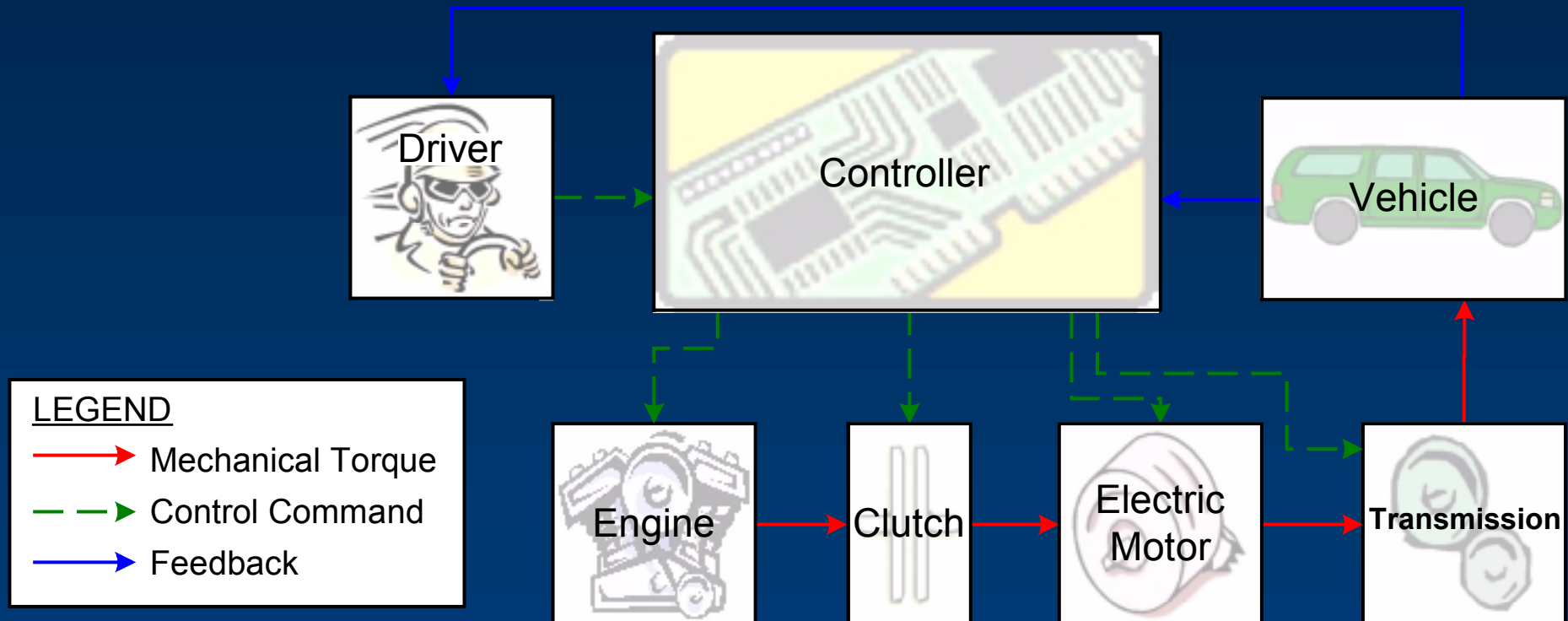
Approaches to Powertrain Control Development

In-Vehicle

Simulation
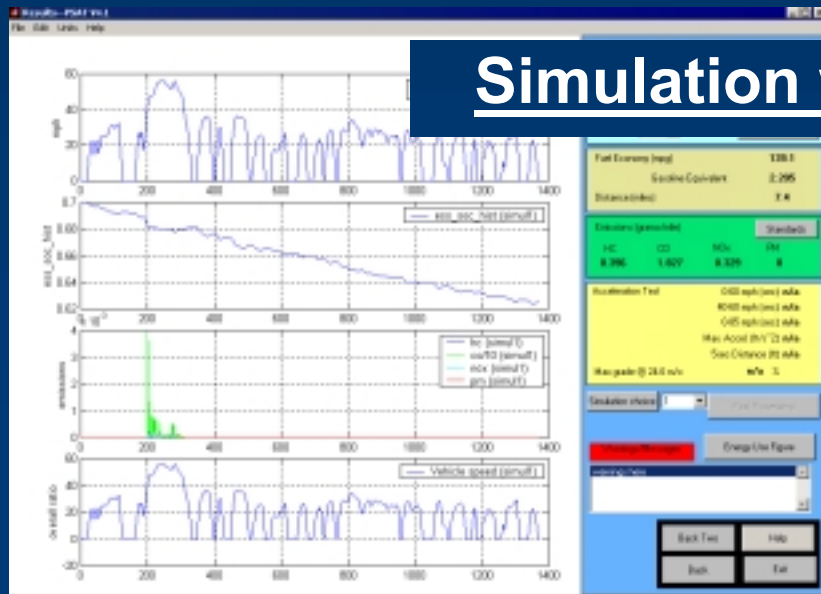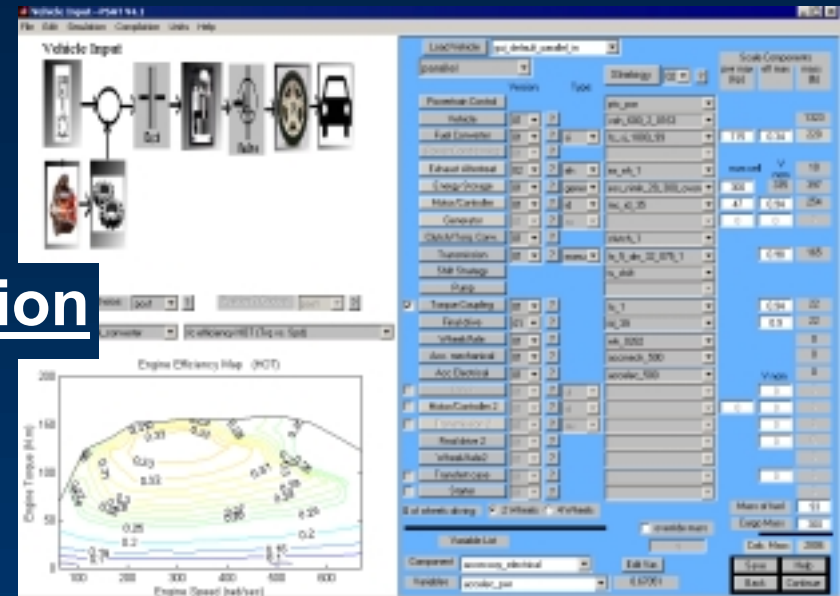
Simulation with Vehicle Application

Simulation with Vehicle Application

Simulation

- **Develop/Test New Algorithms in Simulation**

- **Develop/Run Code within Simulation**

Vehicle

- **Program Modeled Controller in Vehicle**

- **Use dSPACE or Other Tool to Automatically Generate Code**

- **Transfer Code Directly to Vehicle Controller**

Development of Powertrain Code within PSAT
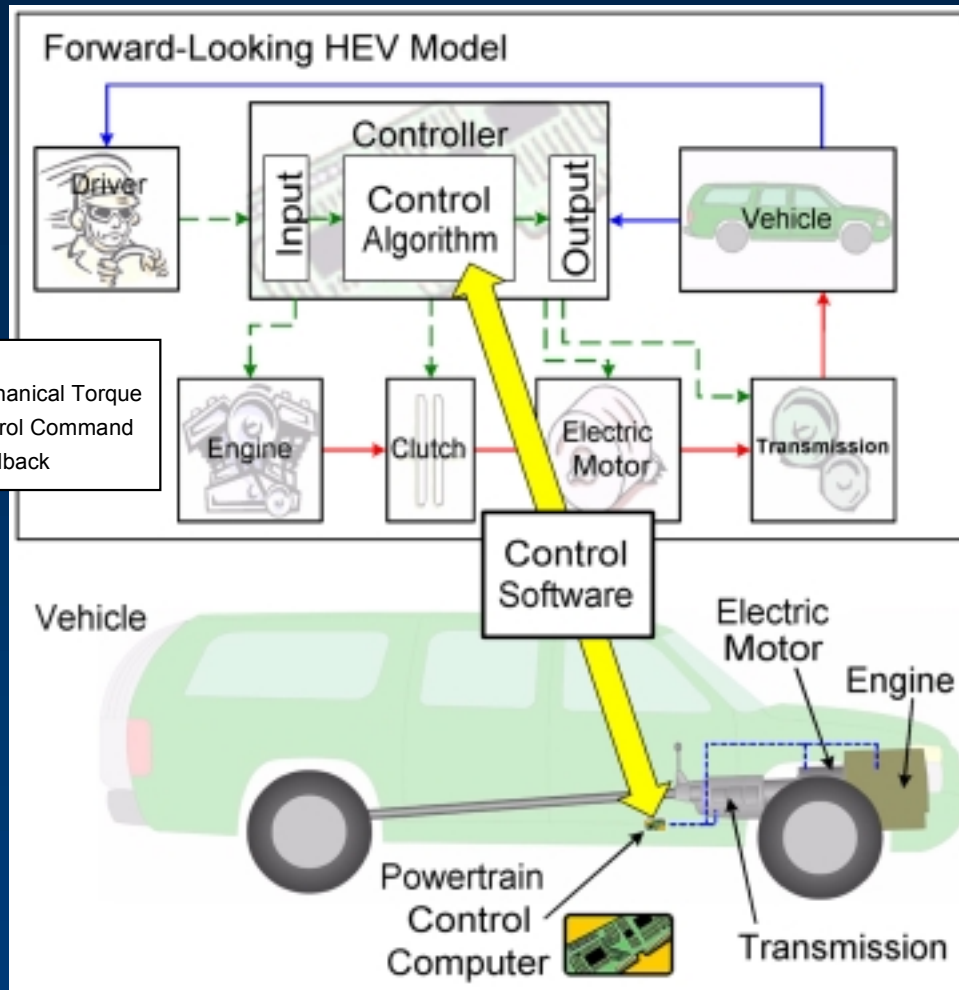
- **Compiled PCM Code as Simulink S-Function**
  - Modified Code to Compile as S-Function or Controller Executable
  - Input/Ouput Method Changed; Controller Algorithms Remain Same
- **Develop/Test Algorithms**
- **Transfer Improved Code Directly to Vehicle**

Simulink S-Function
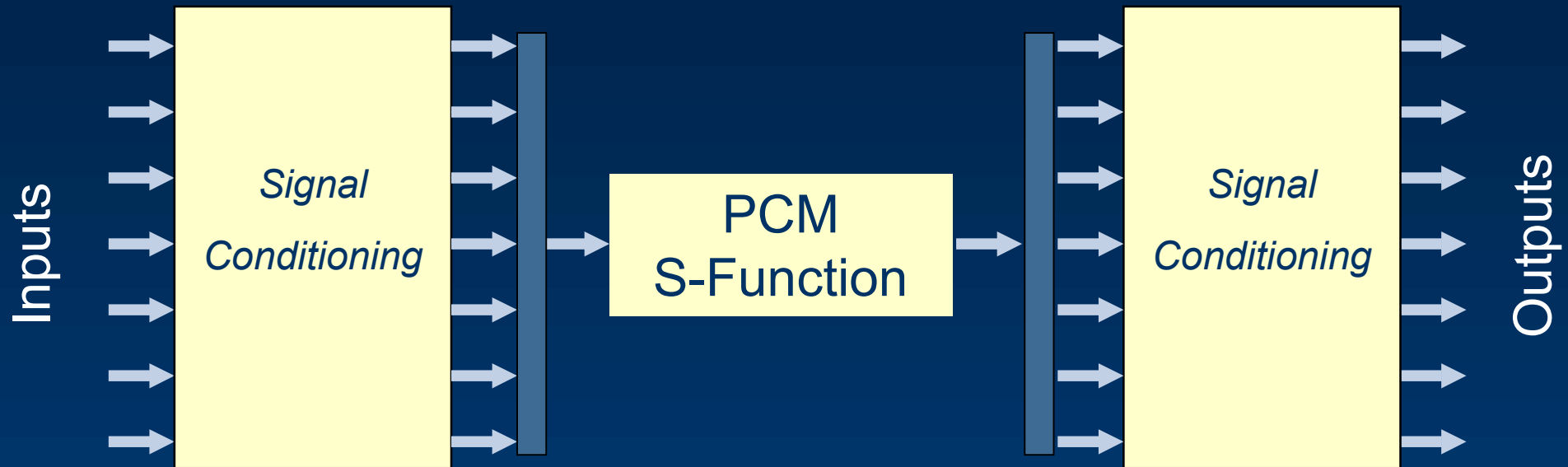
- **S-Function Receives Inputs, Provides Outputs**
- **Inputs/Outputs Mapped to Variables in C Code**
- **10 Inputs; 10 Outputs**

S-Function Test Model
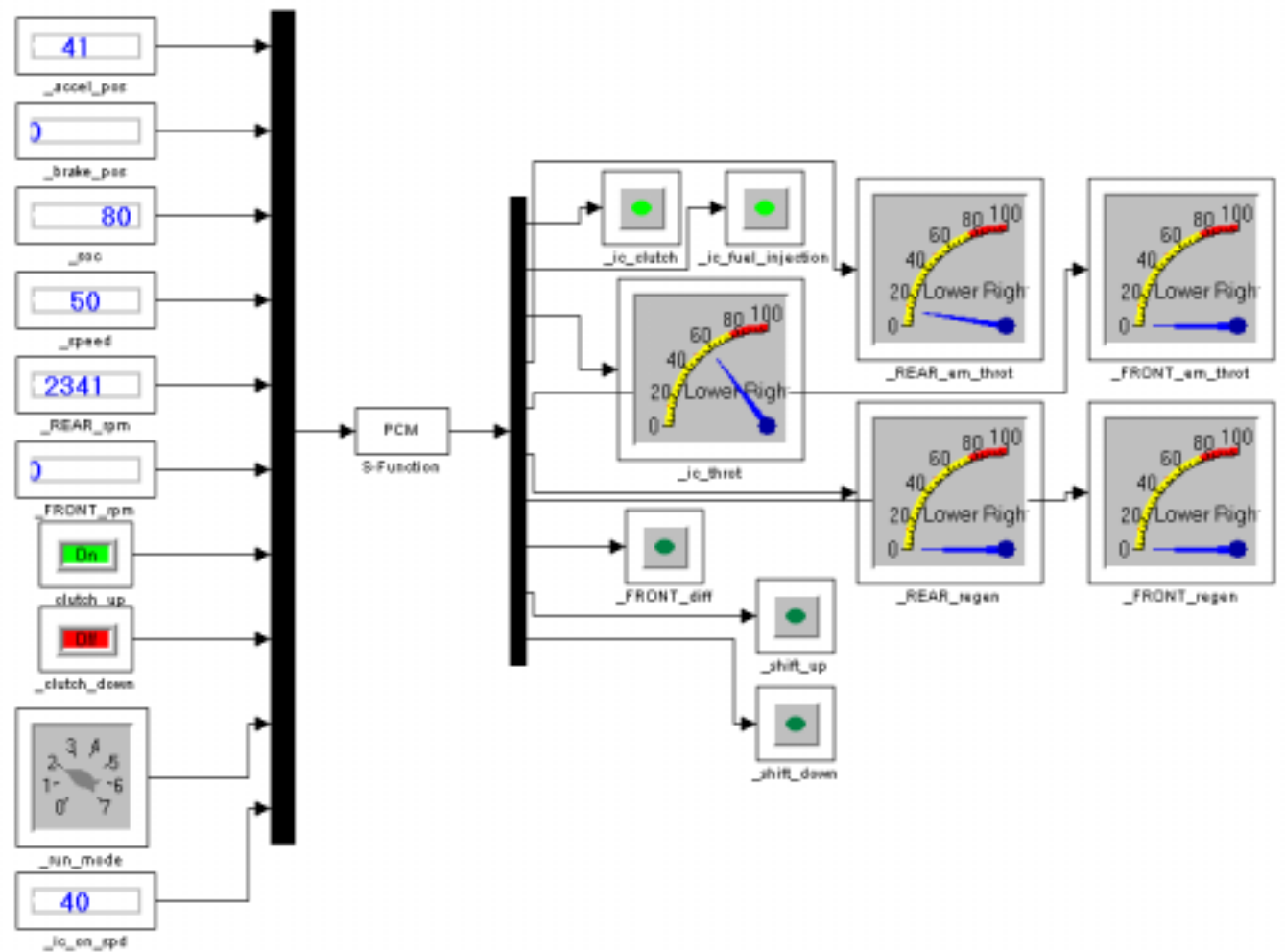
- ◆ **Initial Test to Verify that S-Function Operated Correctly**
- ◆ **Used to Quickly Test New Algorithms**
- ◆ **Test Unusual Input Conditions for Algorithm Robustness**

Implementation of PCM S-Function in PSAT
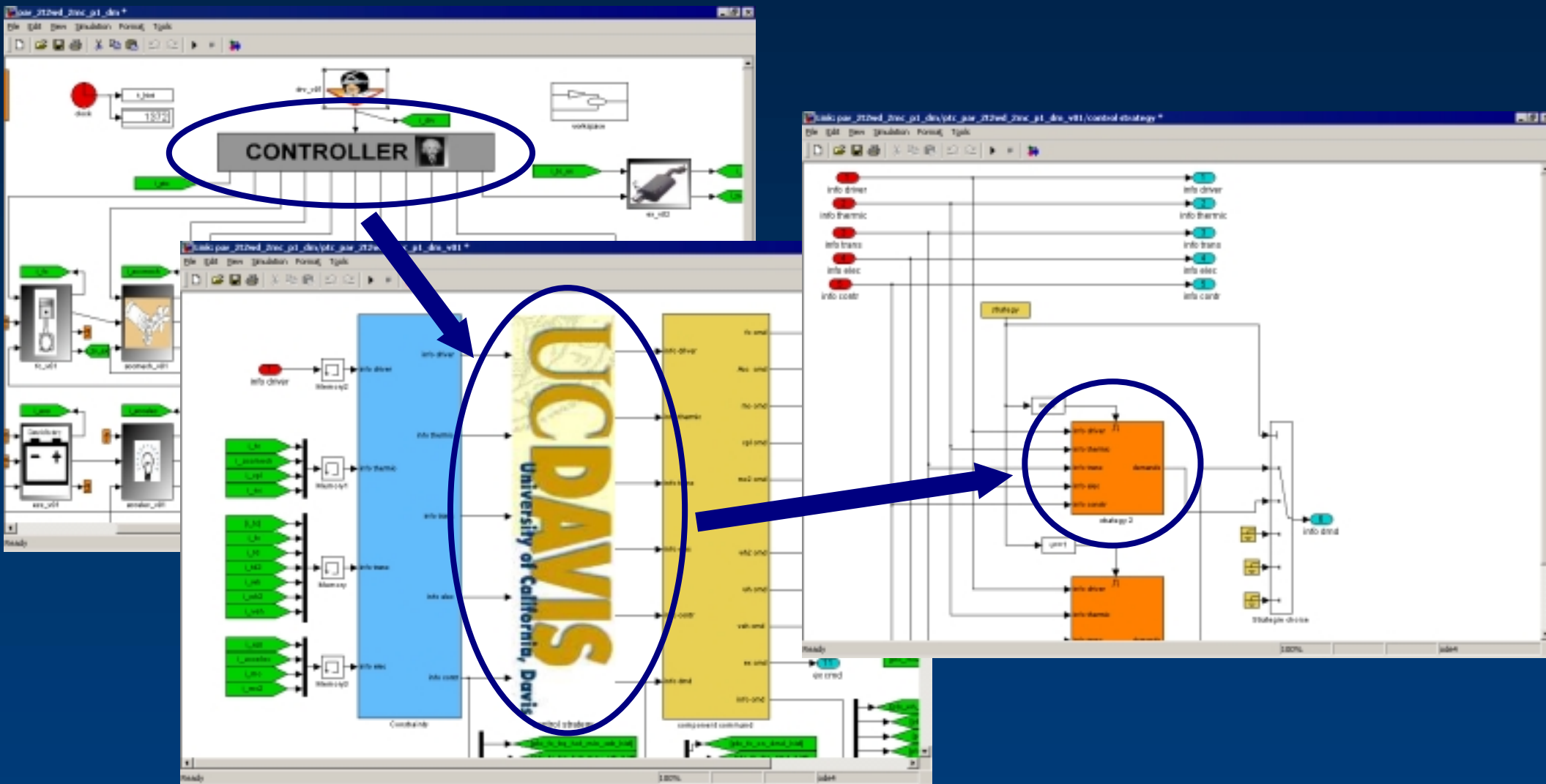
Interface of PCM S-Function with PSAT
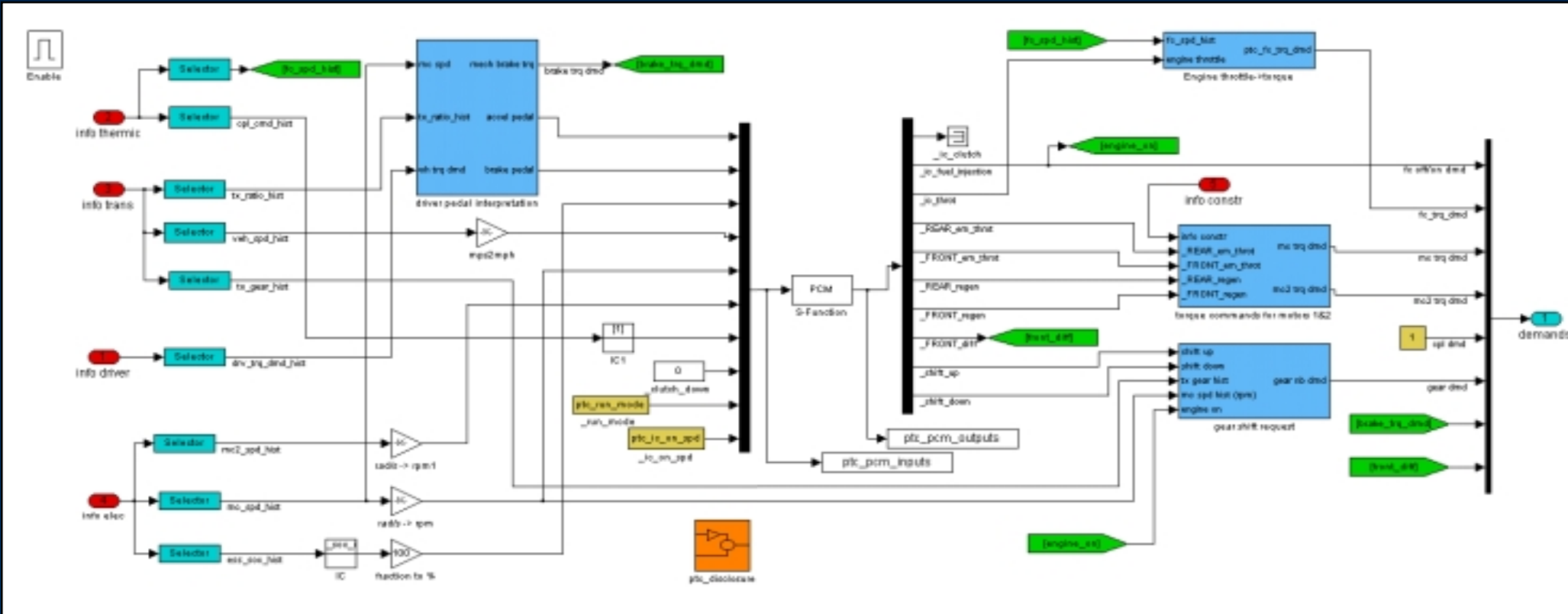
Application to Vehicle: UC Davis *Sequoia*

- **UC Davis 2001 FutureTruck Competition Vehicle**

- **Chevrolet Suburban Platform**

- **Parallel HEV Drivetrain for Rear Wheels**

- **Single-Speed EV Drivetrain for Front Wheels**

UC Davis HEV Center

Sequoia's Drive Modes

- **HEV 2WD**

  Charge Depletion

  Charge Sustaining

  Prevent Engine Fuel Enrichment

  Throttle Rate Limiting

  Gear Shifting Strategy

  Other Techniques in Development

- **EV**

  All-electric

- **Tow/Haul**

  Charge-Sustaining

  Higher Loading

- **HEV 4WD**

  Torque Matched Between Front and Rear Axles

In-Simulation Powertrain Control Strategy Development

- ◆ **Improved Gear Shift Recommendation Algorithm**

- ◆ **Development of Charge-Sustain Sub-Mode**

- ◆ **4WD Mode Development**

Fuel Economy Comparison: PSAT vs. Dynamometer

	Engine Turn On Speed (mph)	PSAT Simulation			FutureTruck Testing
		Gasoline Used (gal)	Electricity Used (DC kWh)	Overall Energy Use	Overall Energy Use
EV-Mode FUDS	N/A	0	2.76	373 Wh/mi *	367 Wh/mi
EV-Mode FHDS	N/A	0	4.11	403 Wh/mi *	403 Wh/mi
HEV-Mode FUDS (charge-sustaining)	15 (initial)	0.310	-0.09	24.2 mpeg**	23.6 mpeg
HEV-Mode FHDS (charge-sustaining)	15 (initial)	0.371	-0.08	27.9 mpeg	27.2 mpeg
HEV-Mode FUDS (charge-depleting)	40	0.053	2.20	55.7 mpeg	N/A
HEV-Mode FHDS (charge-depleting)	40	0.327	0.71	29.1 mpeg	N/A

* Certain modeling assumptions were adjusted to match the EV results to vehicle data. Original results were 379 Wh/mi FUDS and 378 Wh/mi FHDS.

** "mpeg" = miles per equivalent gasoline gallon

UC Davis HEV Center

Conclusions

◆ **Embedded C Code Provides Many Benefits**

Rapid Development and Testing of New Algorithms

Drive Cycle Testing of Simulated Vehicle Using Exact Replica of Powertrain Control Code -- No Controller Modeling Necessary

Transfer Code Developed and Tested on PC Directly to Vehicle Microcontroller without Change

◆ **Continued Work**

Improved Algorithms

CVT Modeling and Shifting Control

Implementation of Embedded C Software within PSAT to Facilitate Hybrid Electric Vehicle Powertrain Control Strategy Development

Robert Schurhoff and Avernethy Francisco
Hybrid Electric Vehicle Center
University of California, Davis

ABSTRACT

UC Davis successfully modeled its hybrid-electric FutureTruck 2001 vehicle, *Sequoia*, using a modified version of PSAT 4.1. As a method to improve vehicle modeling and facilitate control strategy development, *Sequoia's* C-language powertrain control code was embedded within PSAT using a Simulink S-Function. This allowed accurate simulation of several different modes of vehicle operation, including charge-depletion and charge-sustaining strategies, while avoiding the task of programming a model of the controller in Simulink. Improvements were made to the control algorithms by altering the C code and simulating the changes in PSAT. The final algorithms were transferred, unchanged, directly to the vehicle controller for immediate operation and testing. The PSAT results were partially validated by comparing simulation output to vehicle test data. Through the use of embedded C code, PSAT has become a valuable tool for the development of powertrain control strategies and prediction of fuel economy.

INTRODUCTION

A hybrid electric vehicle (HEV) powertrain control strategy is a set of rules that determines how the vehicle's engine, motor(s), and transmission should react to inputs such as the state of the vehicle and the driver's accelerator and brake pedals. The development of such a strategy is a multi-faceted task that requires balancing different goals such as improved energy efficiency, reduced emissions, and vehicle drivability. Several approaches may be taken in designing and evaluating a control strategy. These include developing the system using a working vehicle platform, using computer simulation tools, or employing a combination of these two techniques. The three development approaches have various benefits and issues, such as the following:

In-Vehicle. The process of developing a control system using a working vehicle is a trial-and-error effort that is time consuming and expensive. It requires a reliable, fully-functioning vehicle; test equipment (including a chassis dynamometer and data acquisition system); and data analysis tools. The development process typically involves driving the vehicle repeatedly according to various drive cycles on a chassis dynamometer. Data (often from various pieces of collection equipment) are then analyzed, leading to an improved control algorithm that is applied to the vehicle and tested following the same process.

Simulation alone. The successful development of a vehicle control strategy within simulation requires a highly detailed model that captures all meaningful effects, such as transient behavior. It is best if the simulation is forward-looking, i.e., the model receives control commands and each component in the model responds to the control signals according to appropriate laws of dynamics. A forward-looking model correctly considers dynamic effects such as time delays and rotational inertia. Although using simulation can be much faster and less expensive than testing in-vehicle, it is never as accurate as testing actual hardware.

Simulation with Vehicle Application. Clearly, the best approach is to develop a control strategy within simulation and then apply the system to an actual vehicle for testing. This method is only accurate if the simulation correctly represents the operation of the vehicle and the control strategy developed within the simulation can be precisely translated to vehicle use. The process of transferring control algorithms typically requires the additional step of translating the control system model from the simulation software language (e.g., Simulink) into a language appropriate for vehicle hardware (e.g., C++). Commercial products such as dSPACE permit the direct transfer of a control system model to a hardware controller. However, such systems are relatively expensive and require the user to program the control system in the simulation software

language. In the opinion of the authors, such programming is unnecessarily awkward and tedious for powertrain control since it typically involves developing complicated, multi-state, time-dependent algorithms in an analog-like environment such as Simulink.

This paper describes the application of an alternative approach to powertrain strategy development where appropriate portions of the vehicle control software are embedded directly in the simulation, improved upon, and later transferred to the vehicle for immediate use. The simulations in this project were performed using PSAT Version 4.1 (non-proprietary).

DESCRIPTION OF TEST VEHICLE

Although the simulation method that was developed is not tied to a particular vehicle configuration, a description of the test vehicle is provided here as background information. The explanation also illustrates how several different modes of vehicle operation can be simulated using a single control system model.

The HEV control strategy development for this project was performed with a specific vehicle in mind: the UC Davis 2001 FutureTruck* competition vehicle, named "*Sequoia*." *Sequoia* is a four-wheel drive parallel hybrid electric sport-utility vehicle based on the 2000 Chevrolet Suburban platform. The truck primarily uses a charge-depleting control strategy that maximizes all-electric driving and minimizes energy consumption, but it is also capable of charge-sustaining to provide extended range.

Powertrain Configuration

Sequoia uses separate drive trains for the front and rear axles of the vehicle. The rear powertrain is an in-line parallel hybrid configuration that employs two clutches, an electronically-actuated one between the electric motor and the engine and another that is activated by the driver and located between the electric motor and the transmission. The powertrain, illustrated schematically in Figure 1, features a 95 kW 4-cylinder gasoline engine and a 75 kW DC brushless electric motor.
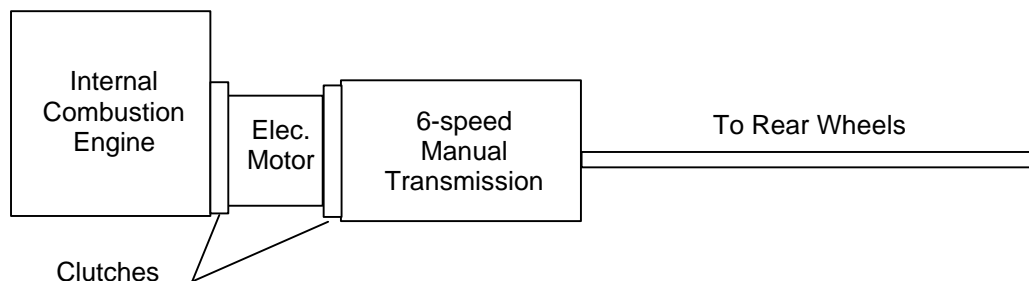
Figure 1. Schematic of Rear Powertrain

The front powertrain, shown in Figure 2, is electric-only with a single-speed gear reduction. This drive system may be decoupled from the front wheels by an electronically-controlled actuator. This powertrain utilizes a separate 75 kW DC brushless electric motor.
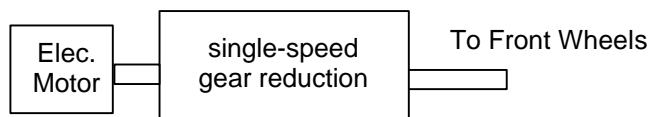
Figure 2. Schematic of Front Powertrain

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* FutureTruck 2000-2001 was a university-level competition sponsored by General Motors and the Department of Energy. For more information about this and upcoming competitions, visit www.futuretruck.org.

Powertrain Control Strategy

Sequoia's Powertrain Control Module (PCM) uses a combination of charge-depletion and charge-sustaining control strategies. During city driving at high battery State-of-Charge (SOC), *Sequoia* operates as an Electric Vehicle (EV). Upon reaching engine turn-on speed, the powertrain transitions from all-electric operation to assisted-engine operation. At highway speeds or at a low battery SOC, the vehicle uses the engine to decrease the rate of battery depletion. At 20% SOC, the vehicle shifts to charge-sustaining operation. The engine control strategy is illustrated in Figure 3.
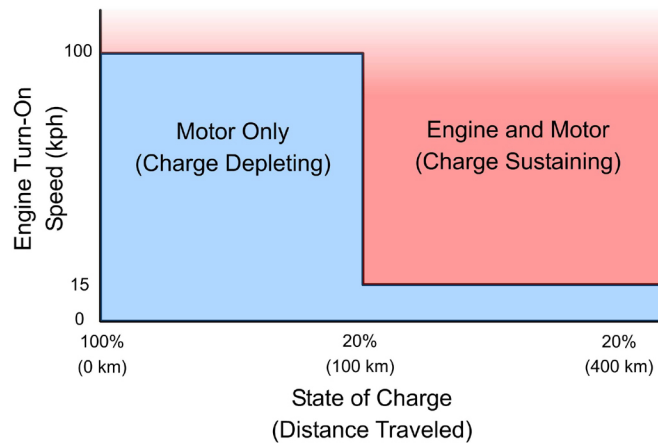
Figure 3. Engine Control Strategy

Sequoia's control strategy minimizes greenhouse gas and regulated tailpipe emissions. Four operating modes accommodate different driving needs: Normal, EV, Tow/Haul, and 4WD. Normal mode is optimized for maximum efficiency, since it is used for the majority of miles driven. The other modes are designed for performance in specific situations. All modes use regenerative braking to recover the kinetic energy of the vehicle.

NORMAL (HEV 2WD) MODE – Normal mode primarily uses a charge-depletion control strategy. If the battery is sufficiently discharged, the controller switches to charge-sustaining mode. Normal mode focuses on minimizing energy usage and emissions by preventing engine enrichment, reducing emissions by limiting the engine throttle rate of change, and using an automated gear shifting strategy.

EV MODE – The driver may select EV Mode to force the vehicle to operate on electric power only. Such operation may be desirable for local driving or commute travel that consists of highway driving within *Sequoia's* all-electric range. EV Mode utilizes the gear-shifting strategy of Normal Mode to minimize energy consumption. If the battery becomes depleted, the vehicle automatically switches to charge-sustaining Normal Mode.

TOW/HAUL MODE –Tow/Haul mode is engaged by the driver when extended towing capability is needed. This mode uses a charge-sustaining control strategy to maintain sufficient reserve battery storage for hill climbing and acceleration under higher load.

HEV 4WD MODE - The 4WD powertrain control strategy requires careful consideration because of *Sequoia's* two separate powertrains. The rear powertrain operates with a multi-speed transmission while the front drivetrain utilizes a single gear reduction, causing the front and rear torque split to change as the transmission is shifted. The PCM recognizes the current transmission gear setting and sets the motor commands appropriately so that equal torque is transmitted to each wheel. The accelerator pedal sensitivity is reduced at low settings to enhance drivability.

IMPLEMENTATION OF EMBEDDED C CODE

Modeling of Powertrain Configuration in PSAT

Sequoia is modeled in PSAT using a "Position 1" parallel hybrid configuration (4WD) as follows:
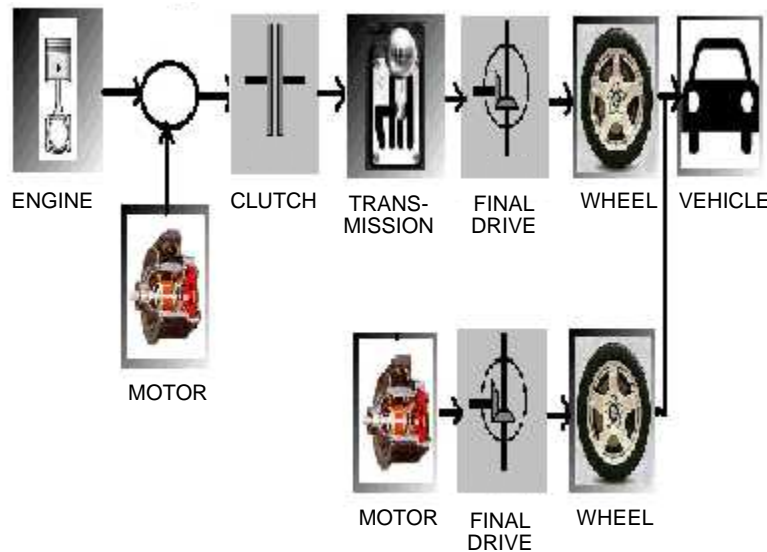
Figure 4. Powertrain Configuration in PSAT

Since *Sequoia* utilizes two clutches while PSAT currently provides the option to use only one clutch, it was necessary to devise a method to instruct PSAT to disconnect the engine from the rest of the powertrain. It was determined that when the engine is disabled in PSAT, it produces zero torque (i.e., no drag) and uses no fuel. Since the engine effectively disappears when commanded "off", the engine engagement clutch between the engine and the electric motor is effectively modeled by using PSAT's engine on/off command. Therefore, for modeling purposes, the available clutch was positioned between the electric motor and the transmission. In reality, certain transient effects occur while the engine is engaging or disengaging. However, these effects are of limited relevance to the overall fuel economy of the vehicle.

Modification of PSAT Control Strategy Model Library

As indicated above, *Sequoia's* control system contains four drive modes (excluding reverse operation) and each mode may contain several different operating states. Properly modeling such a control system is not only tedious but leads to potential inaccuracies. Instead of re-implementing *Sequoia's* entire control strategy in Simulink (the software in which PSAT operates), *Sequoia's* C-language microcontroller code was imported directly into PSAT. The use of C code within PSAT was accomplished using a Simulink S-Function. An S-Function allows a compiled C or Matlab routine to be executed inside Simulink.

Within PSAT's Control Strategy block, the Input/Output signals that are normally routed to the Simulink model of an HEV powertrain controller are instead mapped to variables in the UC Davis control code. During a simulation run, PSAT interfaces with the control code and executes it exactly as the vehicle's PCM does. Instead of receiving input signals from controls and sensors on-board the vehicle, the control code reads information from other portions of the PSAT model. Likewise, the output commands that are normally sent to *Sequoia's* drive components and actuators are instead routed to command the respective component models within PSAT.

The implementation of C code in PSAT was beneficial in many ways. In particular, it allowed further development and testing of *Sequoia's* powertrain control strategy under PSAT using C

programming, allowing a direct transfer of the finalized code to the vehicle without translating from Simulink back to C. An illustration of the process is shown in Figure 5.
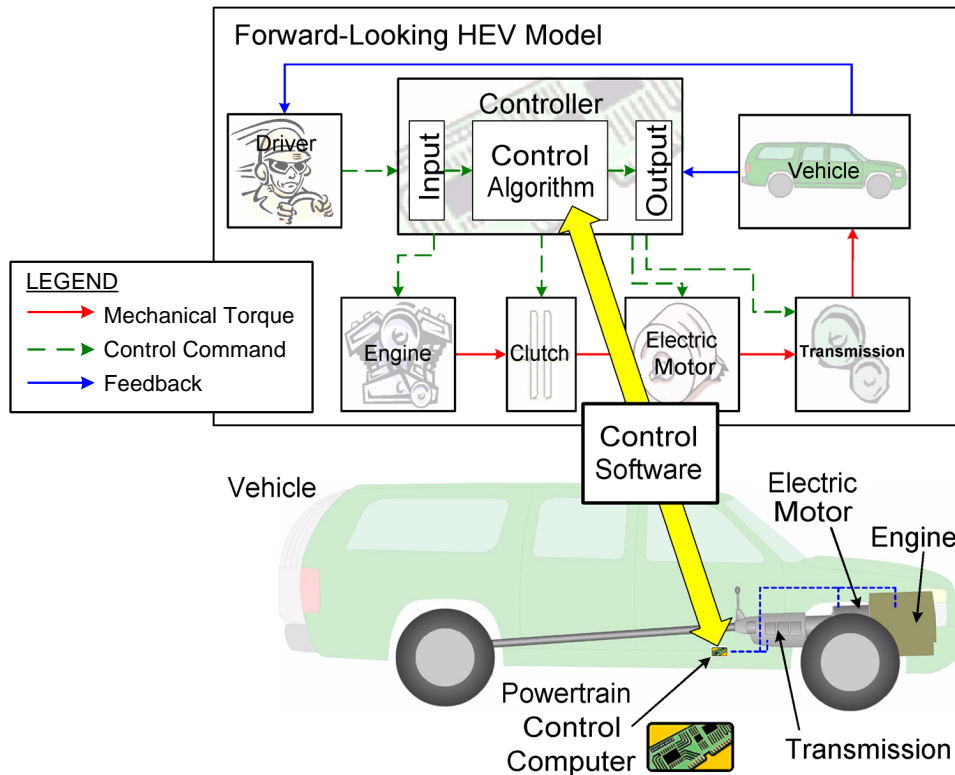
Figure 5. Development of Powertrain Control Code within PSAT

S-Function Development

To implement *Sequoia's* Powertrain Control Module C code within PSAT, a Matlab S-Function was created. The Simulink instruction manual entitled "Writing S-Functions" was referenced in this process, and MathWorks' S-Function template was used ("C Template for a Level 2 S-Function").

The key portions of an S-Function file are the `mdlInitializeSizes` and `mdlOutputs` routines. When a Simulink simulation begins that contains an S-Function, the `mdlInitializeSizes` subroutine of the S-Function is called to initialize the interface between Simulink and the C code. The vehicle PCM's initialization routine is also called from within this function. The `mdlOutputs` function is called during each time step of the simulation. In the PCM S-Function, `mdlOutputs` contains calls to subfunctions that read inputs from Simulink, perform *Sequoia's* HEV control strategy, and send outputs back to Simulink.

The PCM C code was edited to contain sections that are conditionally compiled depending on whether the code is to be implemented in the vehicle or in Simulink. For example, sections of code that interface with the PCM's hardware and communicate with other control modules in the vehicle are compiled when the software will be used in the vehicle. On the other hand, other portions of code that interface with Simulink are compiled when the software is to be used as an S-Function. In either case, the control strategy algorithms that are executed between the input and output routines remain unchanged.

Interface between PCM and Simulink

A simplified schematic of the PCM code interface with Simulink is shown below:
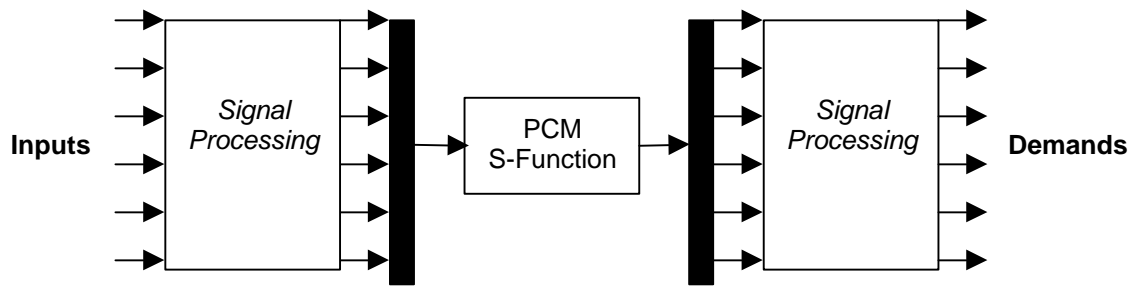
Figure 6. Input/Output Interface with PCM S-Function

There are a total of ten input signals and ten output signals that interface with the PCM. The following tables discuss the purpose of all signals that are inputs and outputs of the PCM.

Table 1. PCM Input Signals

PCM Input	PCM Variable Name	Description
Accelerator pedal position	_accel_pos	Accelerator pedal input from the driver
Brake pedal position	_brake_pos	Brake pedal input from the driver
Battery state-of-charge	_soc	Battery SOC from 0% to 100%
Vehicle speed	_speed	Vehicle speed (mph)
Rear powertrain speed	_rear_rpm	Rear powertrain speed (RPM)
Front powertrain speed	_front_rpm	Front powertrain speed (RPM)
Clutch up	_clutch_up	Set to 1 when the transmission clutch is fully engaged (driver's foot is off the clutch)
Clutch down	_clutch_down	Set to 1 when the transmission clutch is fully disengaged (the clutch pedal is pressed to the floorboard)
Drive mode	_run_mode	An integer value that represents the different powertrain control modes of the PCM, including EV mode, HEV 2WD mode, HEV 4WD mode and Tow-Haul mode
Engine-on speed	_ic_on_spd	This value represents the vehicle speed at which the PCM will turn on the engine during charge-depleting HEV operation. In the actual vehicle, this value is determined within the PCM. The input was added to facilitate testing of different engine-on speeds.

Table 2. PCM Output Signals

PCM Output	PCM Variable Name	Description
Engine engage	_ic_clutch	Commands the position of the clutch between the engine and motor in the primary powertrain. This signal is not used in PSAT.
Fuel injection	_ic_fuel_injection	Turns engine fuel injection system on. This signal is used in PSAT to enable the engine.
Engine throttle	_ic_throt	Commands 0% to 100% (closed to wide open throttle)
Rear motor throttle	_rear_em_throt	Commands 0% to 100% (zero to maximum rear electric motor torque)
Front motor throttle	_front_em_throt	Commands 0% to 100% (zero to maximum front electric motor torque)
Rear regeneration	_rear_regen	Commands 0% to 100% regeneration of the rear motor
Front regeneration	_front_regen	Commands 0% to 100% regeneration of the front motor
Shift up	_shift_up	Set to 1 when the PCM gear-shifting algorithm suggests a transmission gear higher than the current gear
Shift down	_shift_down	Set to 1 when the PCM gear-shifting algorithm suggests a transmission gear lower than the current gear
Front differential	_front_diff	Commands whether or not the front differential is engaged

A Simulink model was created to test the S-Function before it was implemented in PSAT. An illustration of the input/output test model is shown in Figure 7. This model also provides a means to quickly test the behavior of control algorithms without the use of PSAT.
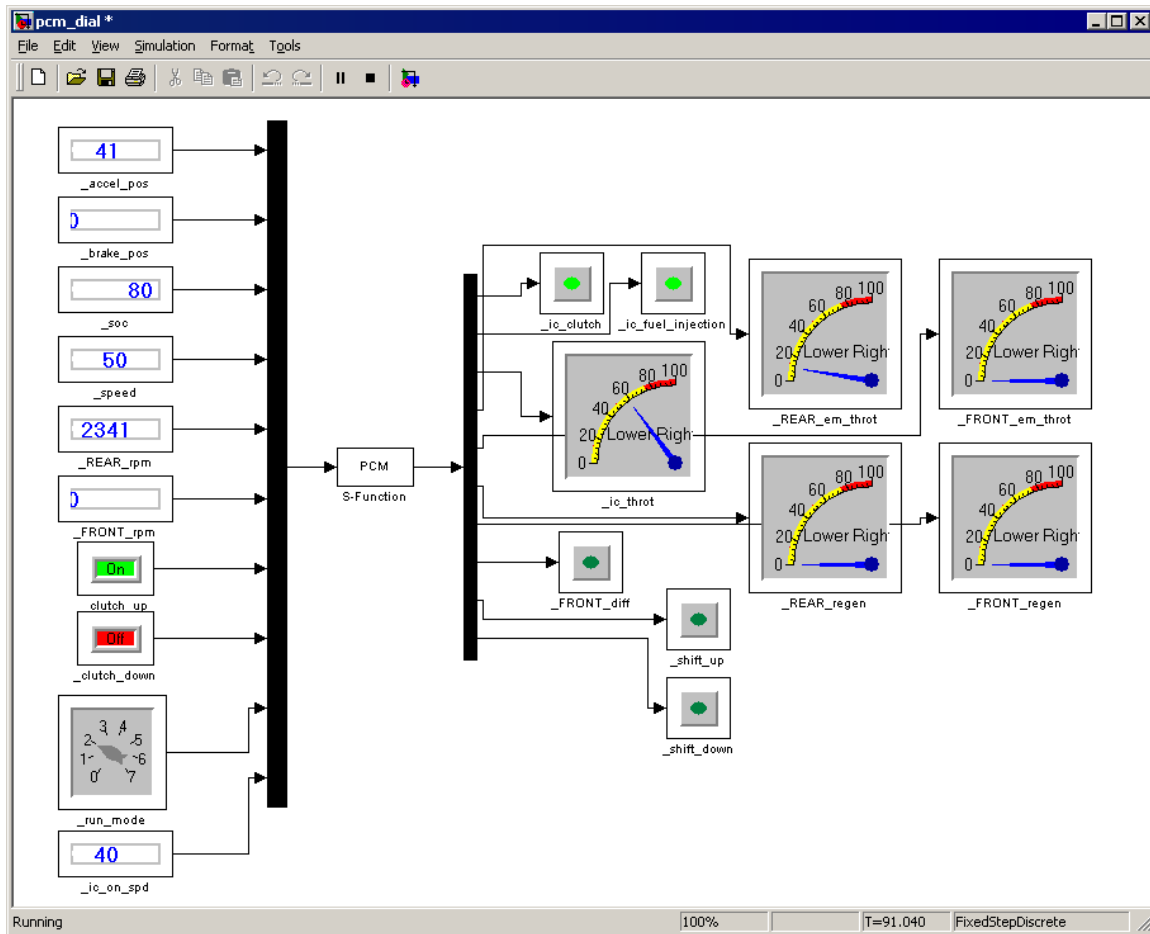
Figure 7. Illustration of PCM S-Function Testing

Interface between PCM and PSAT

The next step was to correctly route the PSAT control signals to the PCM input/output variables. It was also necessary to adjust certain signals so that they properly interfaced with the PCM variables. For example, the PCM outputs the percentage of engine throttle as an engine command, while PSAT requires engine torque as a command. To solve this problem, a lookup table was used to convert engine throttle into engine torque. Another example is the electric motor command. The PCM outputs motor torque commands as a percentage of maximum torque of the motor. These commands are converted into torque before being output to PSAT. The following table discusses each PSAT control strategy signal and how each signal is used in the PCM.

Table 3. Inputs to PSAT Control Strategy

PSAT Control Strategy Input	Signal Name	Description
Engine speed	fc_spd_hist	Used in lookup table to convert PCM throttle command to PSAT torque command
Clutch command history	cpl_cmd_hist	Used to represent the position of the drivers' clutch pedal; routed to the Clutch Up input of the PCM.
Transmission ratio history	tx_ratio_hist	Used by the PCM-PSAT interface block to calculate the accelerator and brake pedal positions
Vehicle speed	veh_spd_hist	The vehicle speed is used for many calculations within the PCM
Transmission gear number history	tx_gear_hist	The previous gear number is used in determining the next gear number
Driver torque demand	drv_trq_dmd_hist	Represents wheel torque demand by the driver; used to create accelerator and brake pedal inputs for PCM
Front motor speed	mc2_spd_hist	Represents front powertrain rotational speed
Rear motor speed	mc_spd_hist	Represents rear powertrain rotational speed
Run mode	ptc_run_mode *	New PSAT signal routed to Drive Mode input of PCM
Engine turn-on speed	ptc_ic_on_spd *	New PSAT signal routed to Engine-on Speed input of PCM
Battery state-of-charge	ess_soc_hist	Routed to SOC input of PCM

* This signal has been added to PSAT by UC Davis

The `ptc_run_mode` and `ptc_ic_on_spd` inputs were added to PSAT to furnish additional input signals required by the PCM. The PCM outputs are converted into the following variables for PSAT's use:

Table 4. Outputs from PSAT Control Strategy

PSAT Control Strategy Output	Signal Name	Description
Engine on	fc_on_dmd	Commands engine to be enabled
Engine torque	fc_trq_dmd	Engine torque requested (N-m)
Front motor torque	mc2_trq_dmd	Front motor torque requested (N-m)
Rear motor torque	mc_trq_dmd	Rear motor torque requested (N-m)
Clutch command	cpl_dmd	Not used. Set to 1.
Gear demand	tx_gear_dmd	Transmission gear request
Brake demand	brake_trq_dmd	Mechanical brake torque demand (N-m)
Front differential	front_diff *	Enables front differential

* This signal has been added to PSAT by UC Davis

The `front_diff` signal commands the vehicle to lock or unlock the front differential. This control enables 2WD modes to be simulated using a 4WD vehicle model configuration in PSAT. The signal interfaces with a modified model of the front powertrain final drive.

Figure 8 illustrates the final interface between the PCM S-Function and PSAT.

RESULTS

Control Strategy Development

The use of embedded C controller code in PSAT promoted the rapid development and testing of powertrain operating strategies while the test vehicle build was still being completed. With the capability to simulate the vehicle in a variety of conditions including full drive cycles, problems could be uncovered and solved before the code was ever tested in the actual vehicle. Furthermore, the second-by-second simulation results provided a method of analysis and visualization of vehicle operation that facilitated the development of improved control strategies.
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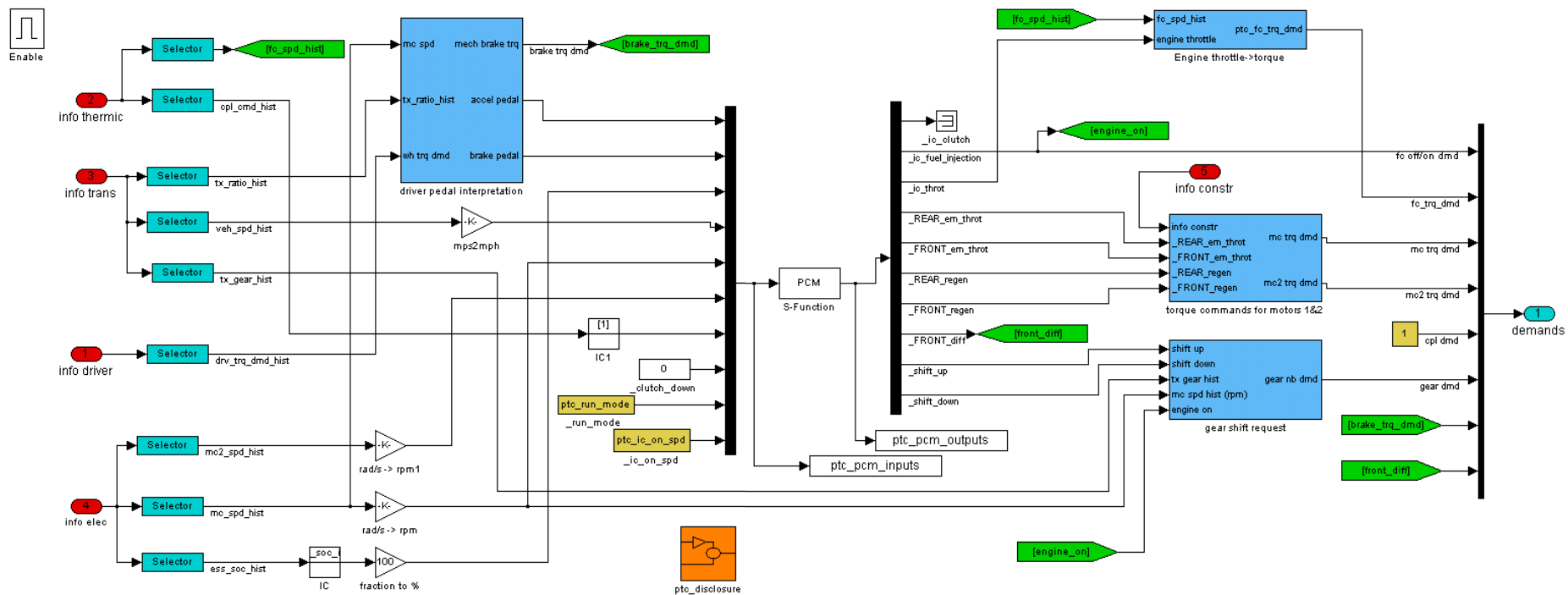
Figure 8. Interface of PCM S-Function with PSAT

PSAT simulation with embedded code assisted the following developments to *Sequoia's* control algorithms:

- ¨ An improved four-wheel drive mode was tested. The testing uncovered an incorrect equation in the algorithm that was corrected prior to operation of the vehicle.
- ¨ The gear shift recommendation algorithm was expanded and improved. The strategy was simulated using various drive cycles to test its operation.
- ¨ A new, more sophisticated charge-sustaining algorithm was developed and simulated on various drive cycles. When the code was transferred to the vehicle, the in-vehicle controller behaved exactly as simulated.

In summary, the simulation process permitted extensive evaluation of different driving conditions before the vehicle was actually operated. The duration of the control strategy development cycle was significantly reduced.

Fuel Economy Simulation Results

Once the control strategy was properly modeled in PSAT, certain parameters were altered and new algorithms were devised to study the effects on fuel economy. The simulations focused on testing the Federal Urban Driving Cycle (FUDS) and Federal Highway Driving Cycle (FHDS). The following table compares the results of PSAT simulations to data collected during actual vehicle testing at the FutureTruck 2001 competition. *Sequoia* was tested on a chassis dynamometer at General Motors' Milford Proving Grounds in June 2001. Since *Sequoia* is capable of driving as an electric vehicle, it undergoes separate testing for EV and HEV modes (comparable to the SAE J1711 Full Charge Test and Partial Charge Test, respectively).

The PSAT results were partially validated by comparing EV-mode simulation output to vehicle test data. Individual component models have not been validated. Initial simulations using known input parameters provided slightly inaccurate results (379 Wh/mi FUDS and 378 Wh/mi FHDS in simulation compared to 367 Wh/mi FUDS and 403 Wh/mi FHDS in vehicle testing). The error may be a result of incorrect consideration of first-order (velocity-dependent) losses. Certain input parameters were adjusted to cause the simulation results to closely match the vehicle performance, as shown in Table 5.

Table 5. Fuel Economy Results

		PSAT Simulation			FutureTruck Testing
	Engine Turn-On Speed (mph)	Gasoline Used (gal)	Electricity Used (DC kWh)	Overall Energy Use	Overall Energy Use
EV-Mode FUDS	N/A	0	2.76	373 Wh/mi *	367 Wh/mi
EV-Mode FHDS	N/A	0	4.11	403 Wh/mi *	403 Wh/mi
HEV-Mode FUDS (charge-sustaining)	15 (initial)	0.310	-0.09	24.2 mpeg**	23.6 mpeg
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HEV-Mode FUDS (charge-depleting)	40	0.053	2.20	55.7 mpeg	N/A
HEV-Mode FHDS (charge-depleting)	40	0.327	0.71	29.1 mpeg	N/A

*   Certain modeling assumptions were adjusted to match the EV results to vehicle data. Original results were 379 Wh/mi FUDS and 378 Wh/mi FHDS.
**   "mpeg" = miles per equivalent gasoline gallon

The charge-sustaining HEV-mode test begins the vehicle at partial battery charge (in this case, 20% SOC) and requires the end-of-test SOC to be within a certain percentage of the initial SOC.

Table 5 shows that the simulation results for these tests match actual test data extremely well (within 3%). In fact, the proximity of the results is surprising and merits further investigation. Since second-by-second test data of energy use (electricity and gasoline) is not currently available, a careful review of mid-test simulation behavior has not yet been completed.

The vehicle is also capable of operating in an HEV mode that engages the engine at a fixed vehicle speed. Such an operating mode is strictly charge-depleting (except during regenerative braking) and is more energy efficient in certain driving situations, such as long trips involving mixed driving. This mode was not tested at the FutureTruck competition. The simulation results in Table 5 show that the energy economy of this mode falls between the EV and charge-sustaining HEV modes.

CONCLUSION

As a method to improve vehicle modeling and facilitate control strategy development, C-language code was embedded within PSAT using a Simulink S-Function. The use of embedded C code provides the following benefits:

- ¨ Very accurate model representation of vehicle powertrain controller. Since the same control code is used in the model and the vehicle, there is no need to reprogram a model of the controller in Simulink.
- ¨ Simulation of multiple vehicle driving modes (e.g., 2WD or 4WD) using a single interface to the C code
- ¨ Easy testing of unusual input conditions by directly interacting with the inputs and outputs of the S-Function. The Simulink interface is more visual and interactive than most C compiler debugging tools.
- ¨ Rapid prototyping of improved control algorithms
- ¨ Changes to the "modeled" controller (i.e., edits to the C code) can be immediately applied to the vehicle.

Future vehicle modeling work with PSAT will focus on:

- ¨ More closely validating *Sequoia* modeling results using vehicle test data
- ¨ Integrating UC Davis' forward-looking Continuously Variable Transmission (CVT) model in PSAT to properly account for transient effects in CVT vehicles. UC Davis performs CVT research and uses CVTs in two of its current vehicles.
- ¨ Further developing powertrain control strategies for both discrete-gear and continuously variable transmissions in an effort to increase energy economy and reduce tailpipe emissions

The use of embedded vehicle control code increases the utility of vehicle modeling, making it a more meaningful and useful task. Simulation results are more accurate, and testing of new control strategies can be performed rapidly. The application of embedded code in PSAT has made the software a valuable tool for the development of powertrain control strategies and prediction of fuel economy.

ACKNOWLEDGMENTS

Impact of Data Capture on Simulation Speed for Large Scale Models (ADVISOR/PSAT)

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Study Goals

- Large Scale Simulation Models offer potential for capture of large amounts of information
  - Larger information increases scope of application for the simulation models
  - Larger information usually increases computing resource requirements
- The trade-off between "amount" of information presented from the simulation models and the corresponding computing resource requirement is addressed in this study

Outline

- Large Scale Models
  - ADVISOR
- Data Capture Methods in Simulation Experiments
  - Current Practice
  - New Paradigm
- Data Capture Experiments
- Conclusions

Large Scale Models

- Multiple Configurations
- Multiple Parameterizations
- Multiple Analyses
- Book-shelved modules
- ADVISOR and PSAT are good examples of Large Scale Models

Data Capture needs in ADVISOR

- We will consider the default parallel hybrid electric vehicle configuration in ADVISOR for our studies.

- Currently, ADVISOR has 110 "To Workspace" variables

  – Wide-open Throttle Performance and FTP cycle can be simulated with just 24 variables

- Why carry the burden of all the variables for every analysis?

Data Capture Methods in Simulation Experiments

- Matlab/Simulink Environment
  - Scope blocks
  - Display blocks
  - To Workspace blocks

- Current Practice
  - Data Capture hard-coded with models
    - Sensors attached with hardware
    - Tool Environment reflects legacy of working with hardware
  - For different data collection requirements, we have
    - One model with all data collection objects
    - Multiple models each dedicated to one data collection set

EMMESKAY, INC.

Data Capture Methods in Simulation Experiments

- New Paradigm
  - Maintain Data Capture Information independent of the models
  - Several Data Capture Configurations for a given model
    - Instrumentation information saved (& retrieved) independently
    - Easily shared between project team members
    - Appropriate Level of Instrumentation for any given analysis
  - Enabled by the "**<u>Model Instrumentation Manager</u>**" from Emmeskay, Inc

Model Instrumentation Manager

- GUI for instrumentation and visualization
- Optimized for use of Library-linked elements
  - Seamless mechanism to instrument library-linked elements
  - Scopes allowed inside libraries
  - Multiple instantiations of library-linked elements can be instrumented
- Don't have to "prepare" model after debugging or before sharing with project members

Data Capture Experiments

- Default Parallel Hybrid Electric Vehicle BD_PAR used in ADVISOR
- Cycle FTP (2 cycles) + Acceleration Test runs simulated
  - Model simulated as is
  - Model "stripped" of all "To Workspace" blocks using MIM
  - A much smaller subset of "To Workspace" block instrumented using MIM
  - CPU time elapsed recorded for different computers and software platforms

Demo

Results

Computational Speed Gain through "OptimizedI" Instrumentation

Legend:
- Pentimum II-266MHz, 128MB RAM, Win NT
- Pentium III-930MHz, 256MB RAM, Win 2000

Y-axis: Percentage gain in CPU time
X-axis: Integration Time Step
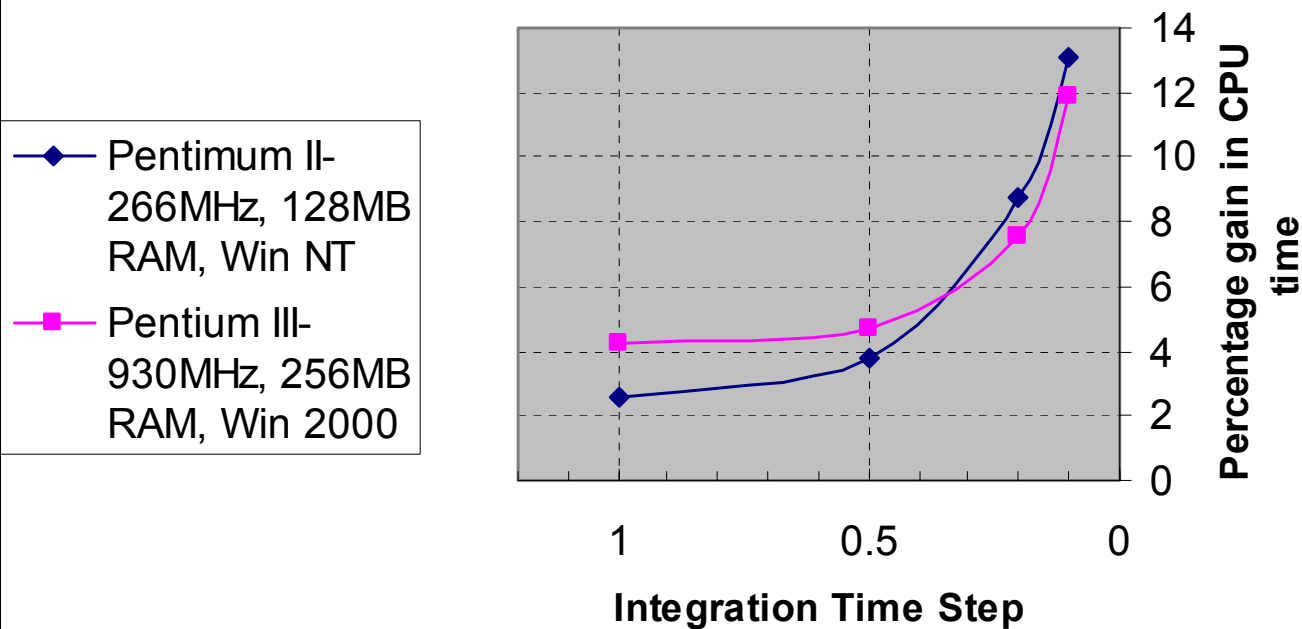
Conclusions

- Data Capture Design Dilemma for Large Scale System Models investigated
- The use of tools such as the Model Instrumentation Manager helps optimize the software design
  - Separation of the data capture information from the core models
  - Application of different data capture sets for different analyses
- Benefits clearly seen when attempting to maximize computing resources
  - Up to 13 % improvements in computing speeds recorded.
  - This is expected to increase exponentially as problem scope becomes larger (e.g. large scale optimizations)

Fuel Cell Hybrid Vehicle Systems Analysis

Degree of Hybrization ADVISOR Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle

Paul Atwood, Stephen Gurski, and Doug Nelson,
Virginia Polytechnic University;
Keith B. Wipke and Tony Markel,
National Renewable Energy Laboratory

Presentation
Paper

Fuel Cell Vehicle System Analysis

Aymeric Rousseau, Rajesh Ahluwalia, Howard Geyer, and Keith Hardy,
Argonne National Laboratory

Overview

- Objectives
- SUV Parameters
- Hybridization Issues
- ADVISOR Vehicle Modeling
- Results
- Conclusions

Vehicle Platforms Considered
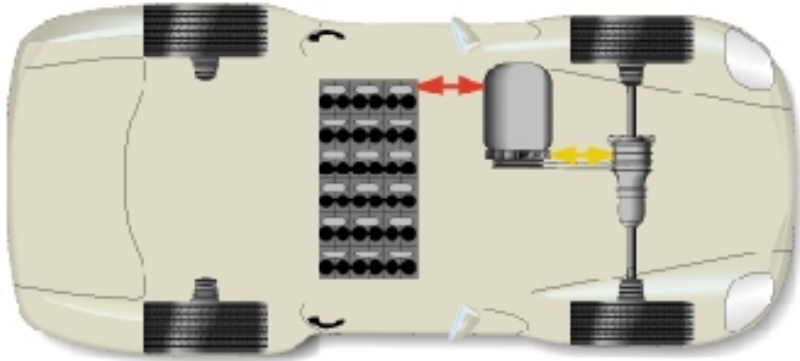
Electric Vehicle
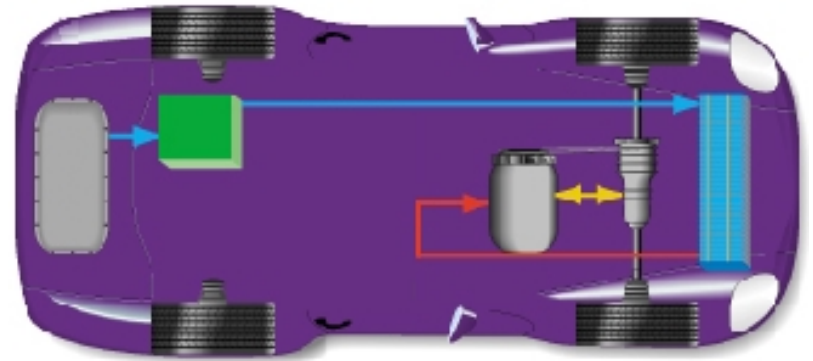
Pure Fuel Cell Vehicle
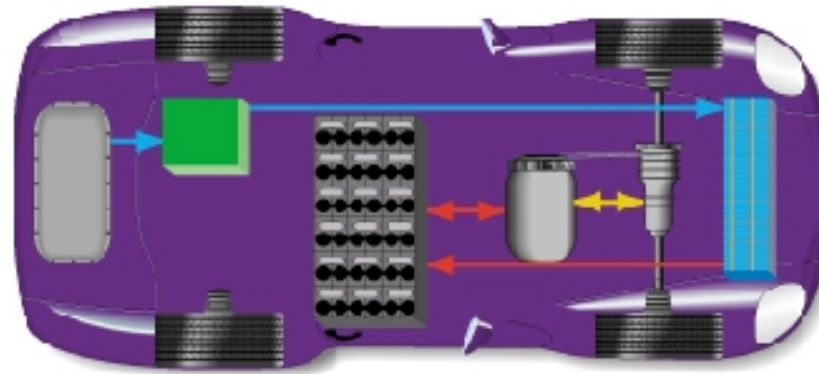
Hybrid Fuel Cell Vehicle

Objectives of Modeling

- Benefits of Hybridization

- Efficiency trade-offs and interactions: fuel cell and battery pack size

- Is there an optimal configuration (including cold-start considerations as future work)

Vehicle Modeling Parameters

Frontal Area (m^2)	**3.17**
C$_D$	**0.45**
C$_{RR}$	**0.008**
Total Mass (kg)	**2900**

Drivetrain Power (kW)	**166**
Accessory Load (kW)	**1.5**

Fuel Cell HEV System

Fuel In

Hydrogen Storage

Heat Rejection

Off Board Battery Charger

Electricity In

Battery Pack

Fuel Cell Stack

Air Compressor

Air In

Front Motor/Inverter

Rear Motor/Inverter

Air Comp Inv

DC/DC Conv

AC Comp Inv

12 VDC Loads
(Pumps, Fans, etc.)

AC Load

Fuel
Air
Electrical
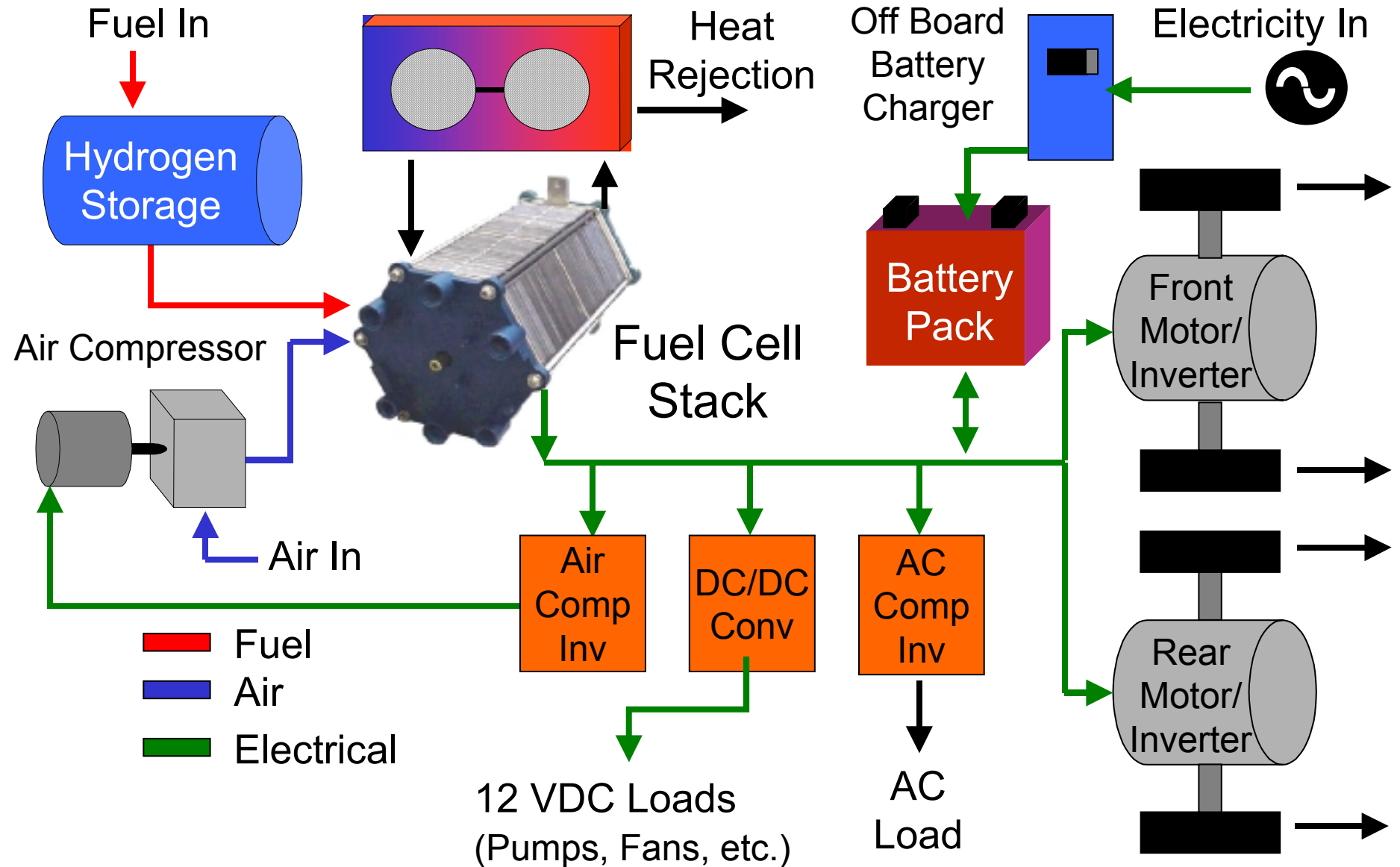
Fuel Cell Stack Performance

Legend: 300 kPa, atm. P

x-axis: current density mA/cm²
y-axis: cell potential (V)

PEM Fuel Cell System

Fuel In

Water In

Hydrogen Storage

Humidify

Air In

Heat Rejection

Controls

To vehicle power bus

Water out

Air Comp Inv

DC/DC Conv

12 VDC Loads
(Pumps, Fans, etc.)

Fuel

Air

Electrical
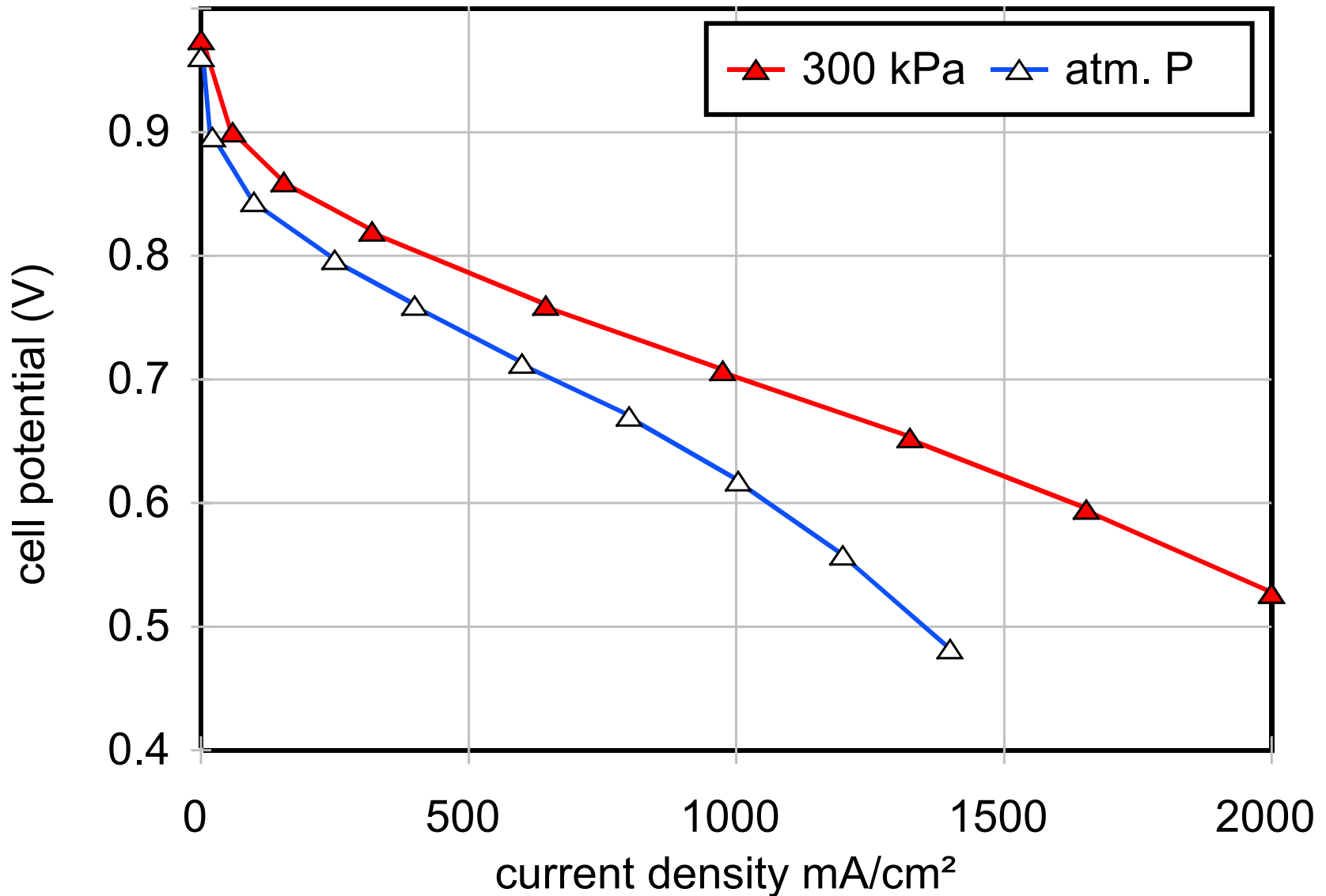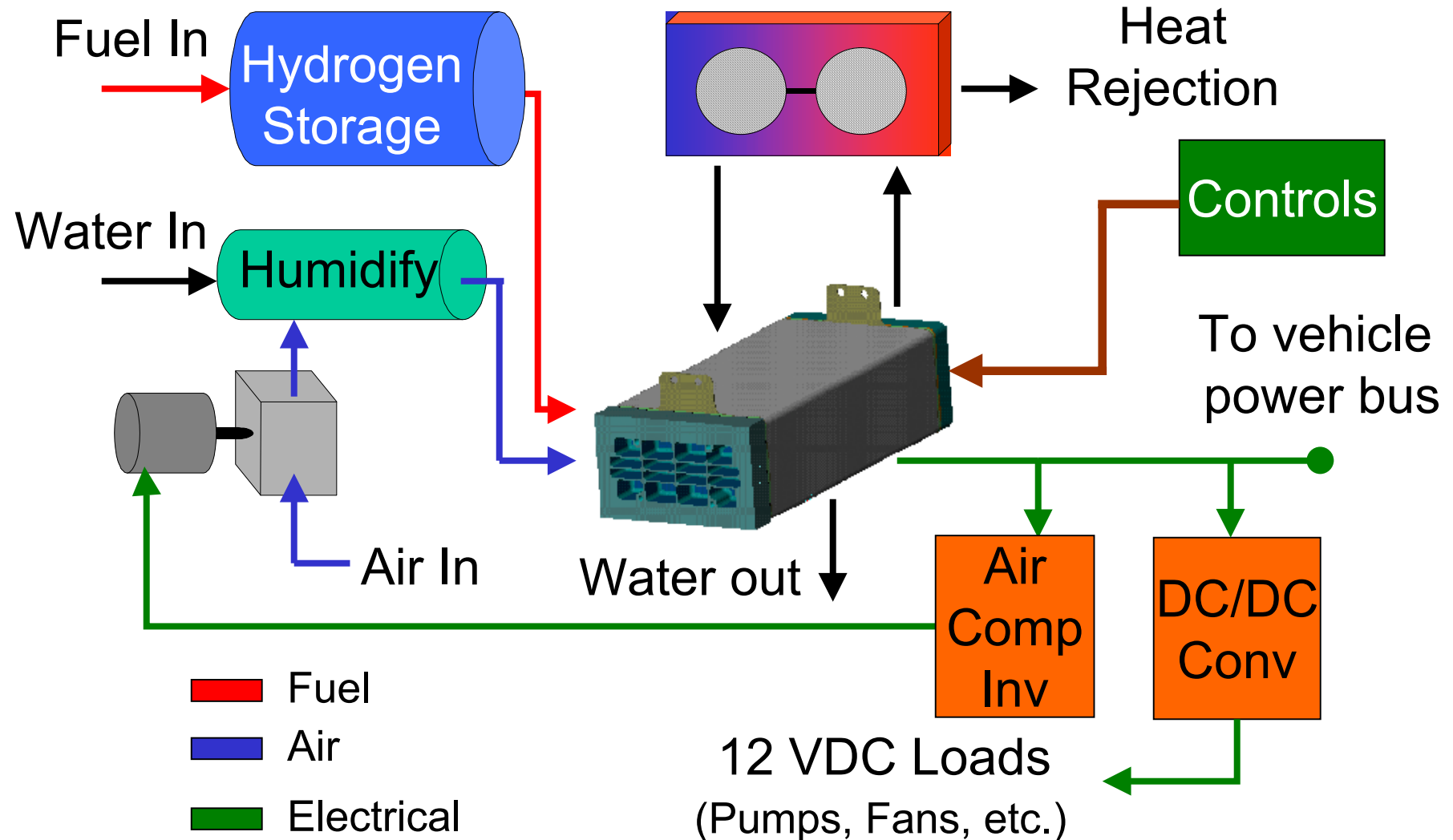
So - Why Hybridize a FCV?

Because of the System...

- Cold Start Power Limitations
- Start-Up (Compressor, Reformer)
- Transient Response

To Improve Fuel Economy...

- Regenerative Brake Energy
- Minimum FC Power Control Strategy

Example 100 kW FC System
scaled from 20 kW 1.8 atm hydrogen
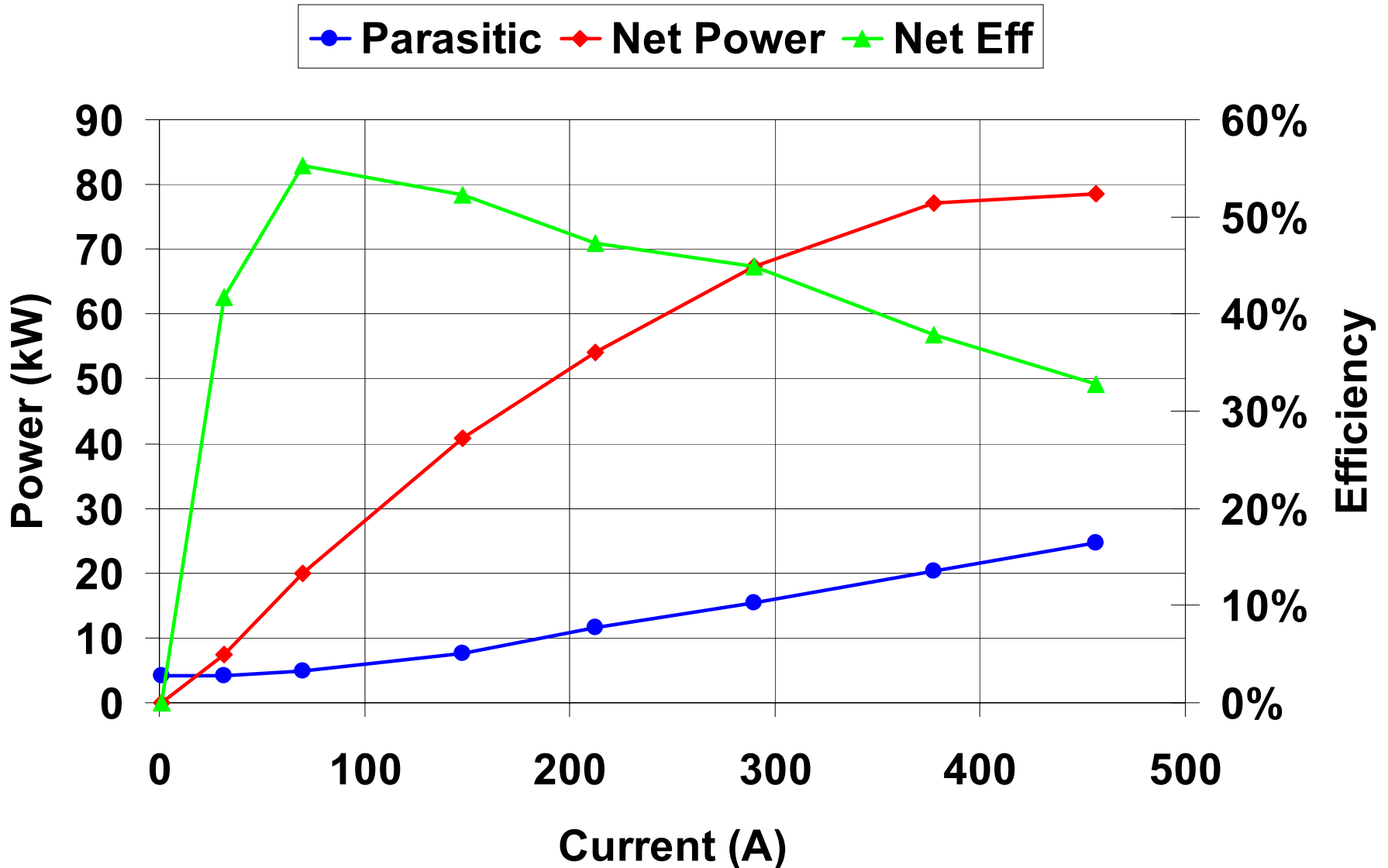
ADVISOR System Model

- Fixed:

  - Total vehicle mass

  - Electric drivetrain

  - Component technology – scaled

- Fuel cell + batteries sized for fixed performance

- Compressed Hydrogen Gas fuel

- No cold start effects considered

Performance

Legend: 0-60 · 40-60 · 0-85 · Grade (10 sec) · Grade (CS)

Y-axis (left): Time (sec) — 0, 4, 8, 12, 16, 20

Y-axis (right): Gradeability (%) — 0, 5, 10, 15, 20, 25

X-axis: Fuel Cell/Battery Ratio (kW/kW) — 0, 0.25, 0.5, 0.75, 1, 1.25
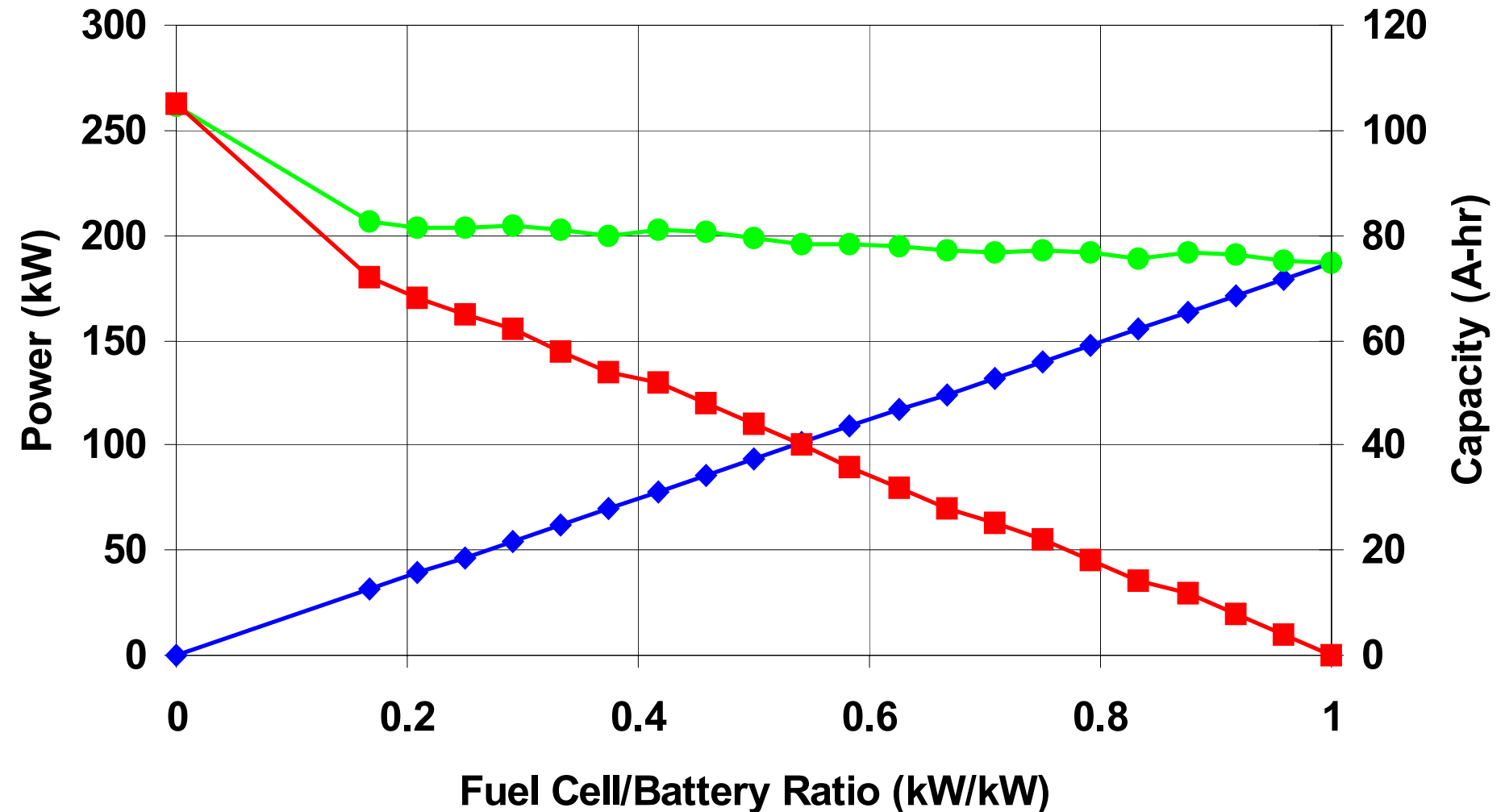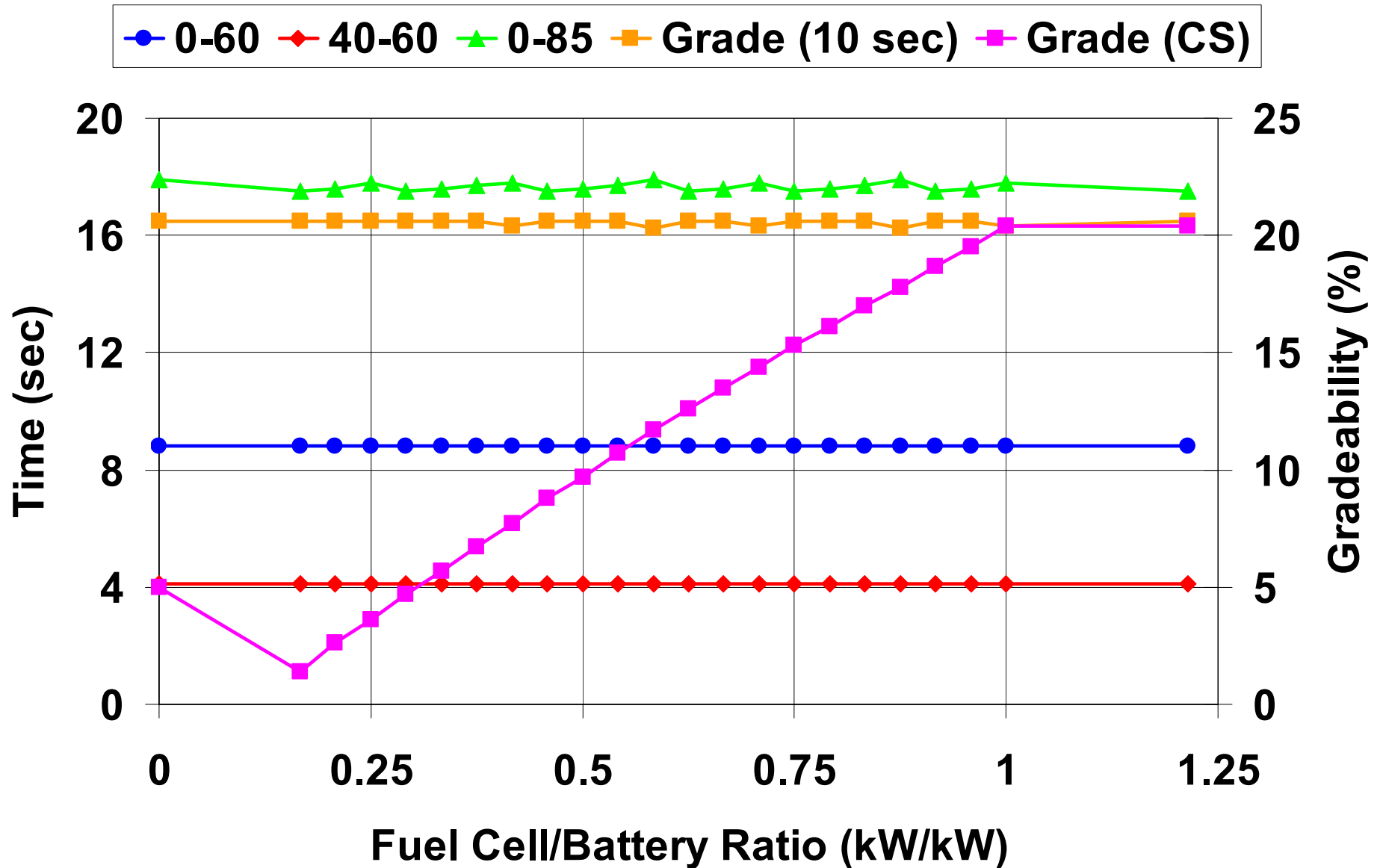
Trailer towing performance
(5900 kg GCVW, 5% Grade)
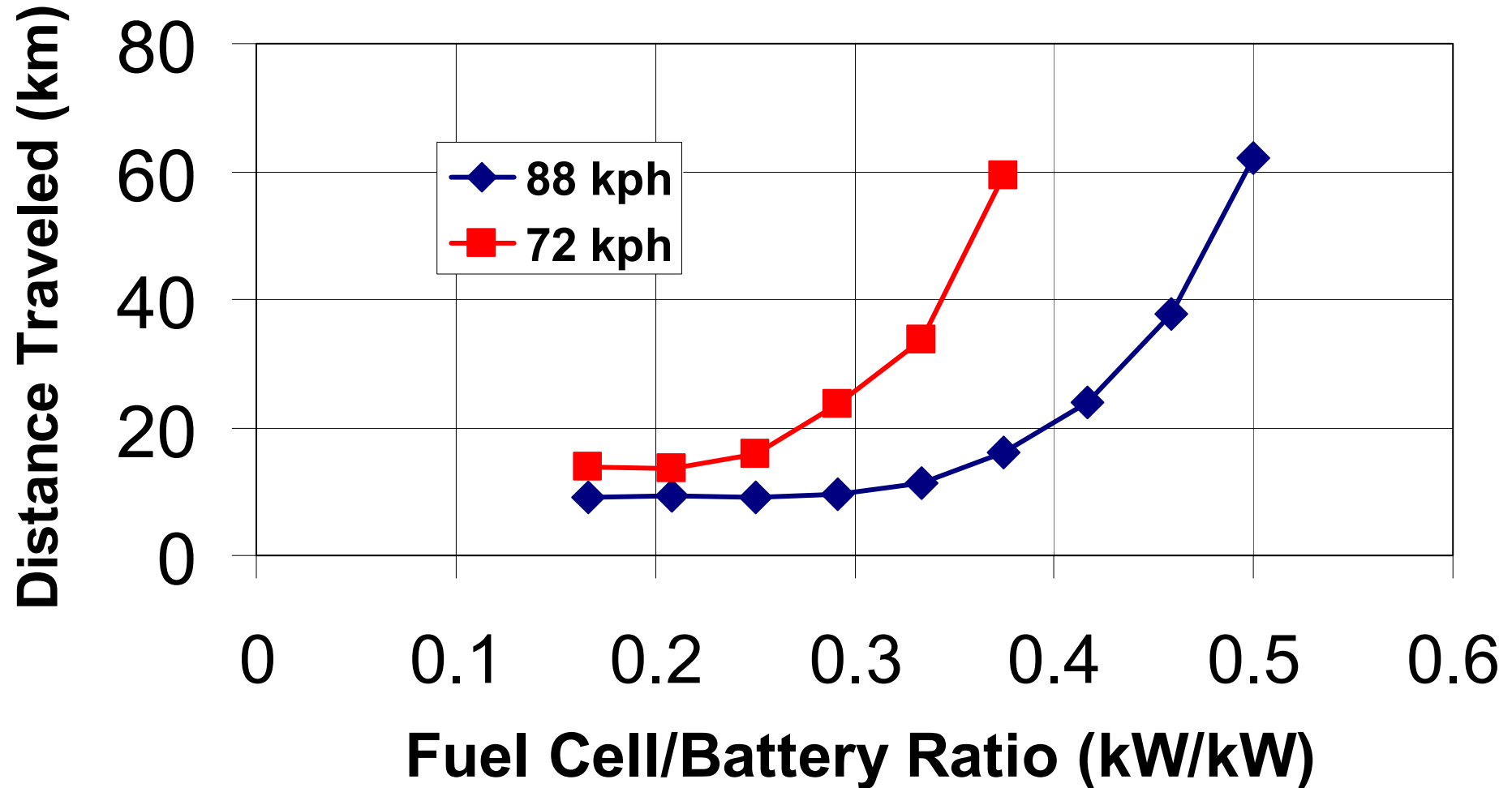
Fuel Economy
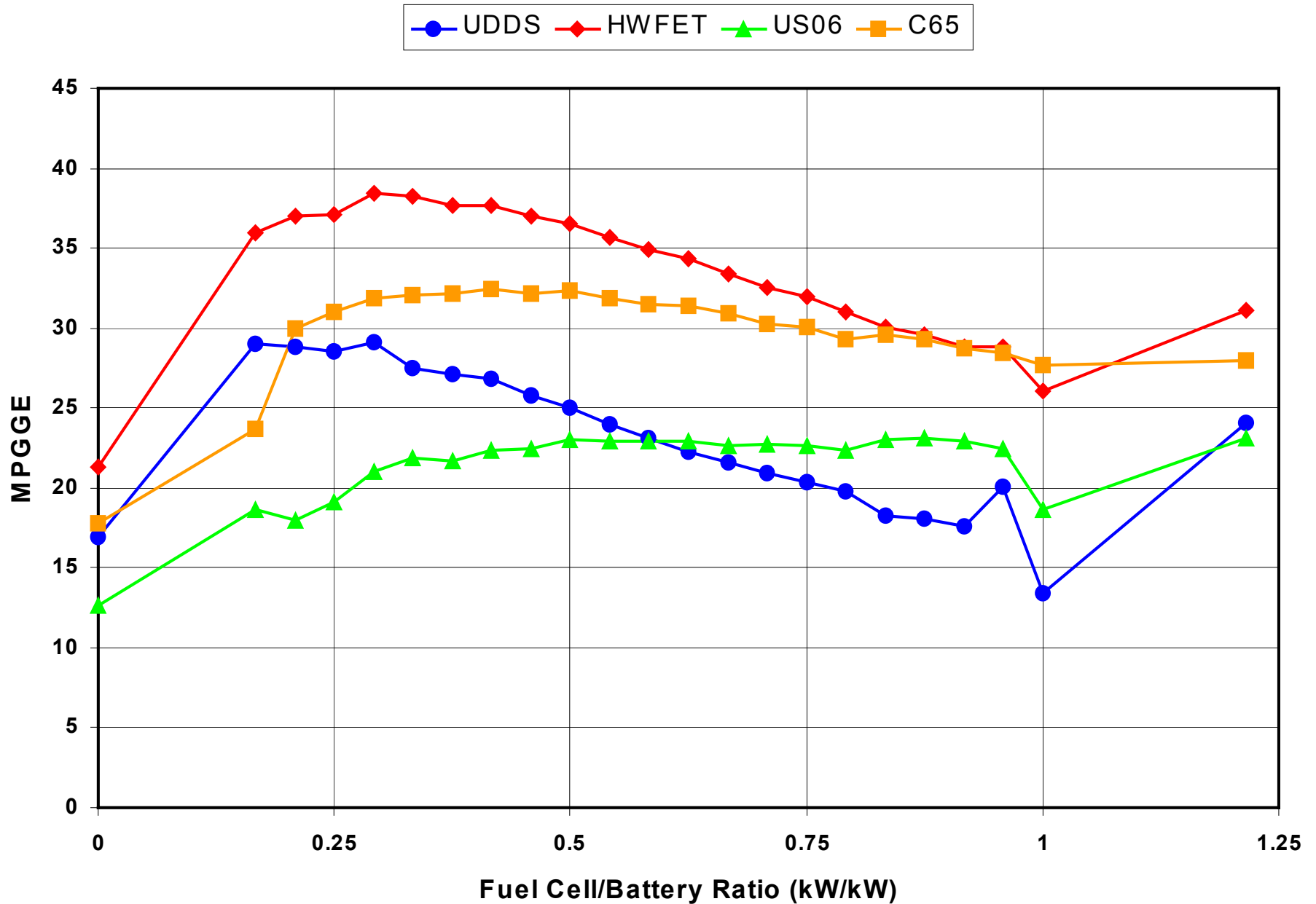
Fuel Economy Results

Depends on fuel cell stack size and efficiency relative to:

– Energy processed through battery round-trip efficiency

– Battery capacity and regenerative energy capture

– Power spectrum for dynamic drive cycles

– Control strategy for Minimum FC power
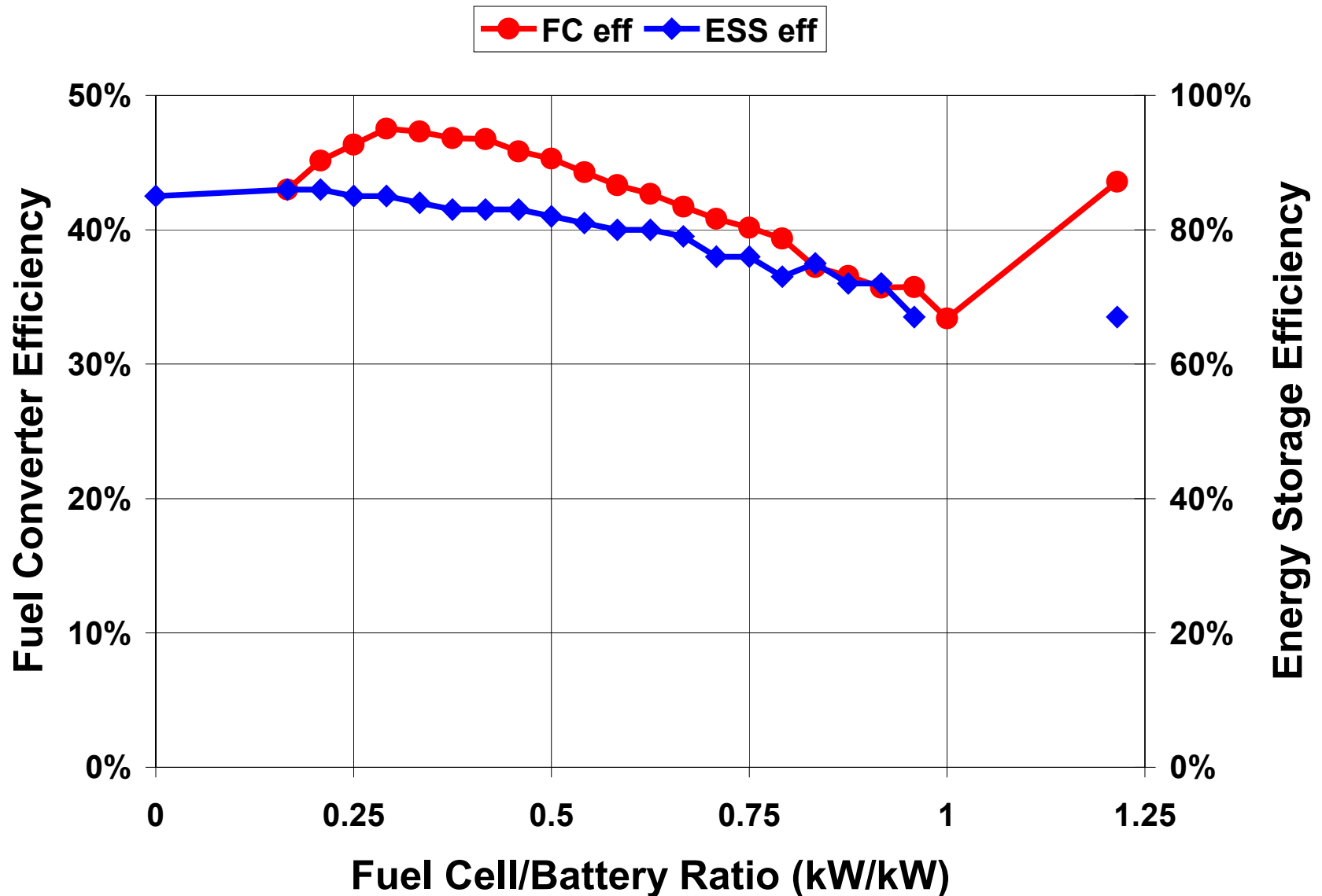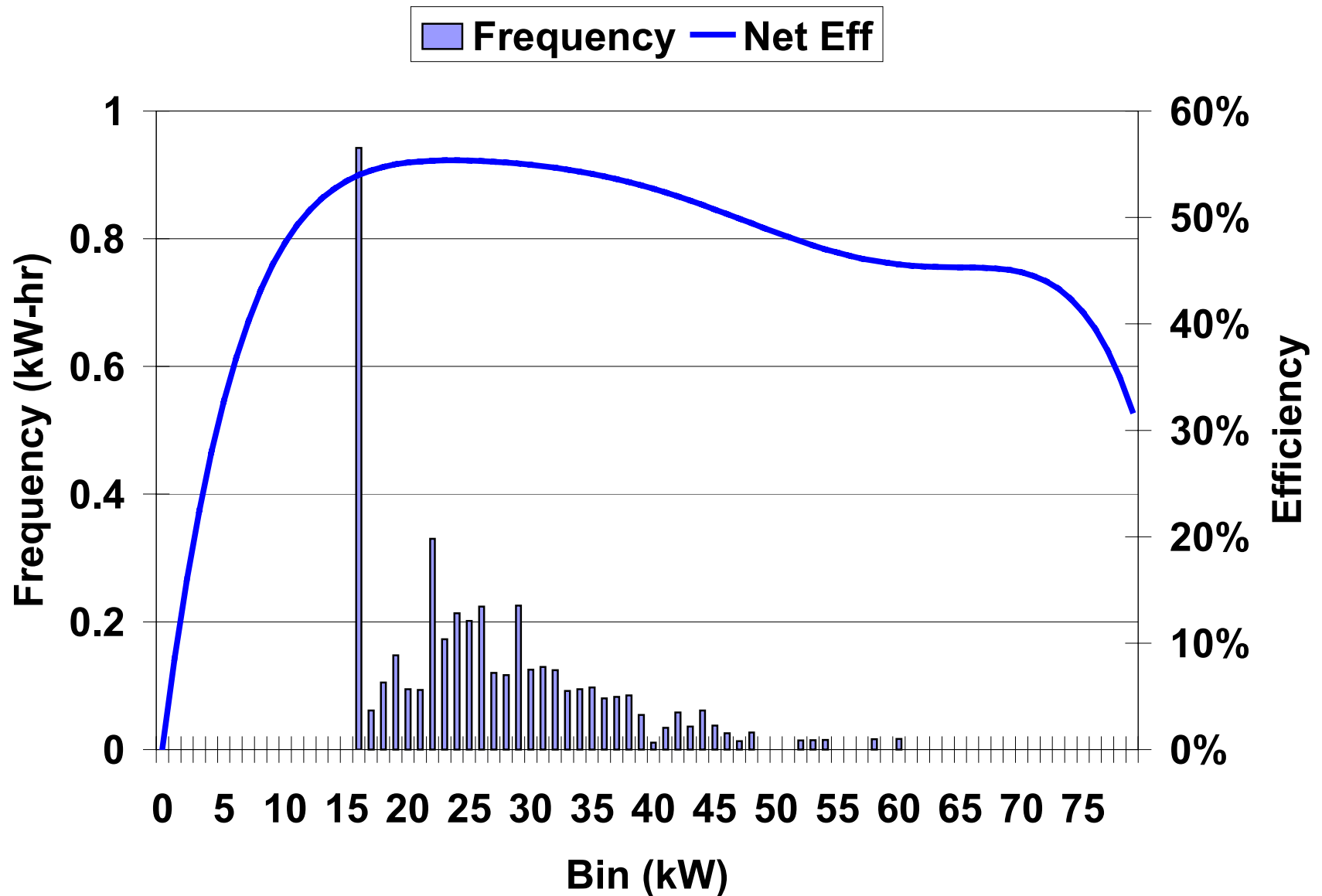
100 kW HWFET FC Spectrum
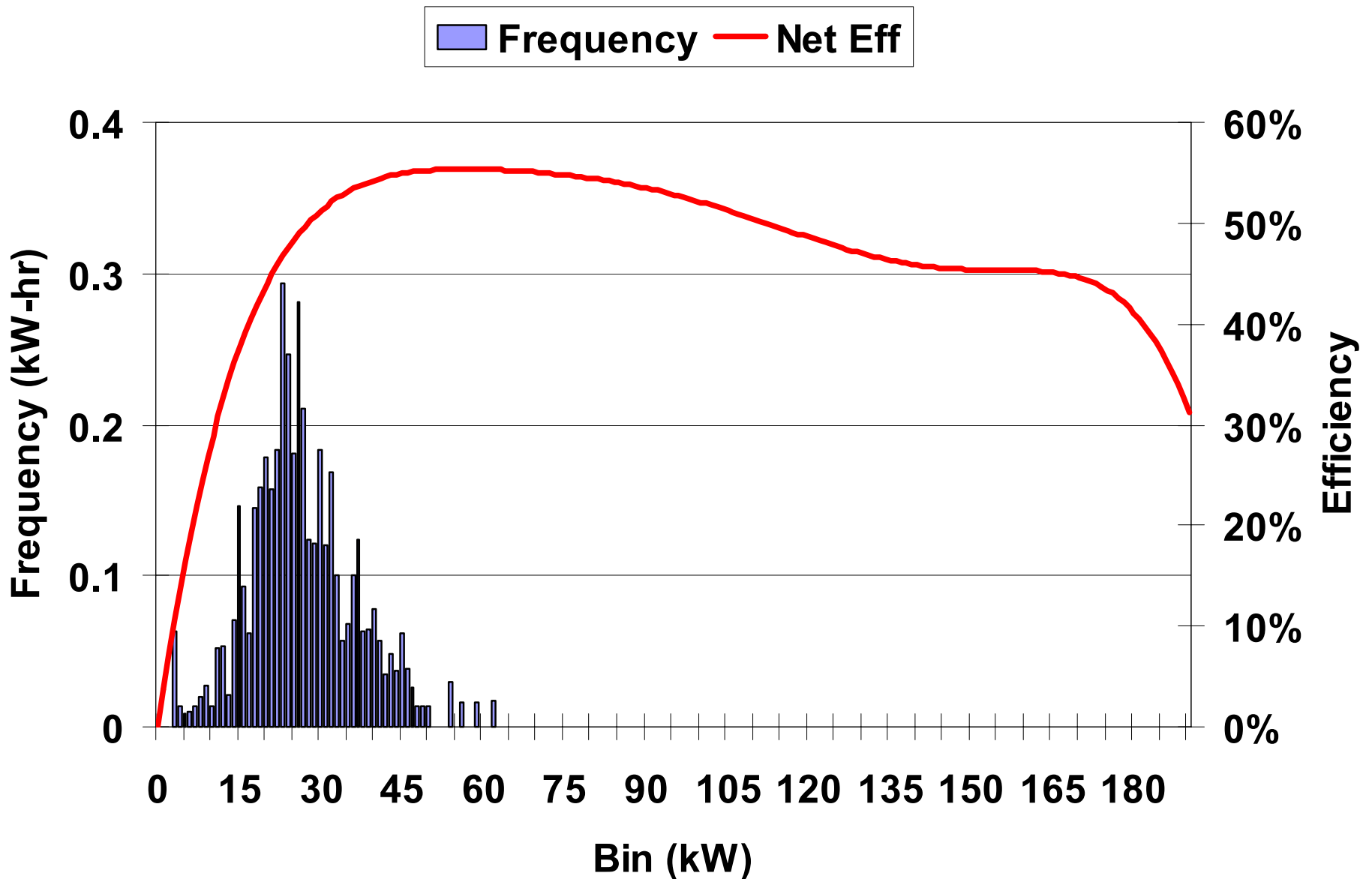
Conclusions

- Hybridization to help with:
  - Regenerative energy capture
  - Cold Start (Future Work)

- Control Strategy
  - Minimum fuel cell power
  - Battery SOC Management

- Fuel Cell Minimum Power Point
  - Prevent excessive operation at light load

Acknowledgements

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     Keith Wipke, Tony Markel, Sam Sprik

- Mike Ogburn, Ford Th!nk

- Hybrid Electric Vehicle Team of Virginia Tech

Degree of Hybridization ADVISOR Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle

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ABSTRACT

An ADVISOR model of a large sport utility vehicle with a fuel cell / battery hybrid electric drivetrain is developed using validated component models. The vehicle mass, electric traction drive, and total net power available from fuel cells plus batteries are held fixed. Results are presented for a range of fuel cell size from zero (pure battery EV) up to a pure fuel cell vehicle (no battery storage). The fuel economy results show that some degree of hybridization is beneficial, and that there is a complex interaction between the drive cycle dynamics, component efficiencies, and the control strategy.

INTRODUCTION

The main benefit of hybridization in a vehicle with an internal combustion engine is load leveling to improve the overall efficiency of the engine operating region. A fuel cell *stack* generally has relatively high efficiency at light load, and a fuel cell *system* may also have good part load efficiency depending on the system parasitic loads (primarily air compressor power). This part load efficiency makes fuel cells attractive for light duty vehicle loads, and would seem to eliminate the need for hybridization. But the start-up of a fuel cell system, including bootstrapping a high-voltage air compressor drive, and cold-start transient response power limitations, may require hybridization. While neither of these important issues are specifically addressed in the current work, the energy efficiency may still be improved through addition of some energy storage. Other reasons for hybridization include the cost, weight and volume of fuel cells relative to batteries, and the capture of regenerative brake energy. Some of these issues have been considered for a 1500 kg sedan by Friedman (1999) and Friedman et al. (2000).

Sport utility vehicles have a relatively large potential for fuel economy improvements. This class of vehicle has some specific uses and drive cycles (such as towing) that

may preclude the downsizing of the main energy converter to improve efficiency.

An ADVISOR simulation model based on validated component models is presented to investigate the potential of hybridization to improve fuel economy of a large sport utility vehicle. The objectives of this analysis are to understand the efficiency interactions of fuel cells and batteries, and determine if there is an optimal configuration.

VEHICLE DESCRIPTION

The large sport utility vehicle (SUV) chosen for this analysis is based on a 2000 four-wheel drive Chevrolet Suburban LT converted to a fuel cell hybrid electric vehicle (FCHEV). For the current modeling, the exterior geometry of the vehicle stays the same, and the conventional internal combustion engine drivetrain is replaced with a fuel cell/battery series hybrid electric drivetrain. The basic vehicle parameters for this class of vehicle are listed in Table 1 below.

Table 1 Large Fuel Cell Hybrid SUV Parameters

Drag Coefficient	0.45
Frontal Area, m^2	3.17
Rolling Resistance Coefficient	0.008
Mass, kg	2900

The total mass shown for the converted FCHEV is set 400 kg higher than the stock vehicle to approximate the increased weight of the fuel cell and battery components, and then held constant for the results given here. The fuel cell system on the vehicle is assumed to be supplied by a compressed hydrogen gas storage system. The present work does not consider the difficult packaging issues of fuel cell components,
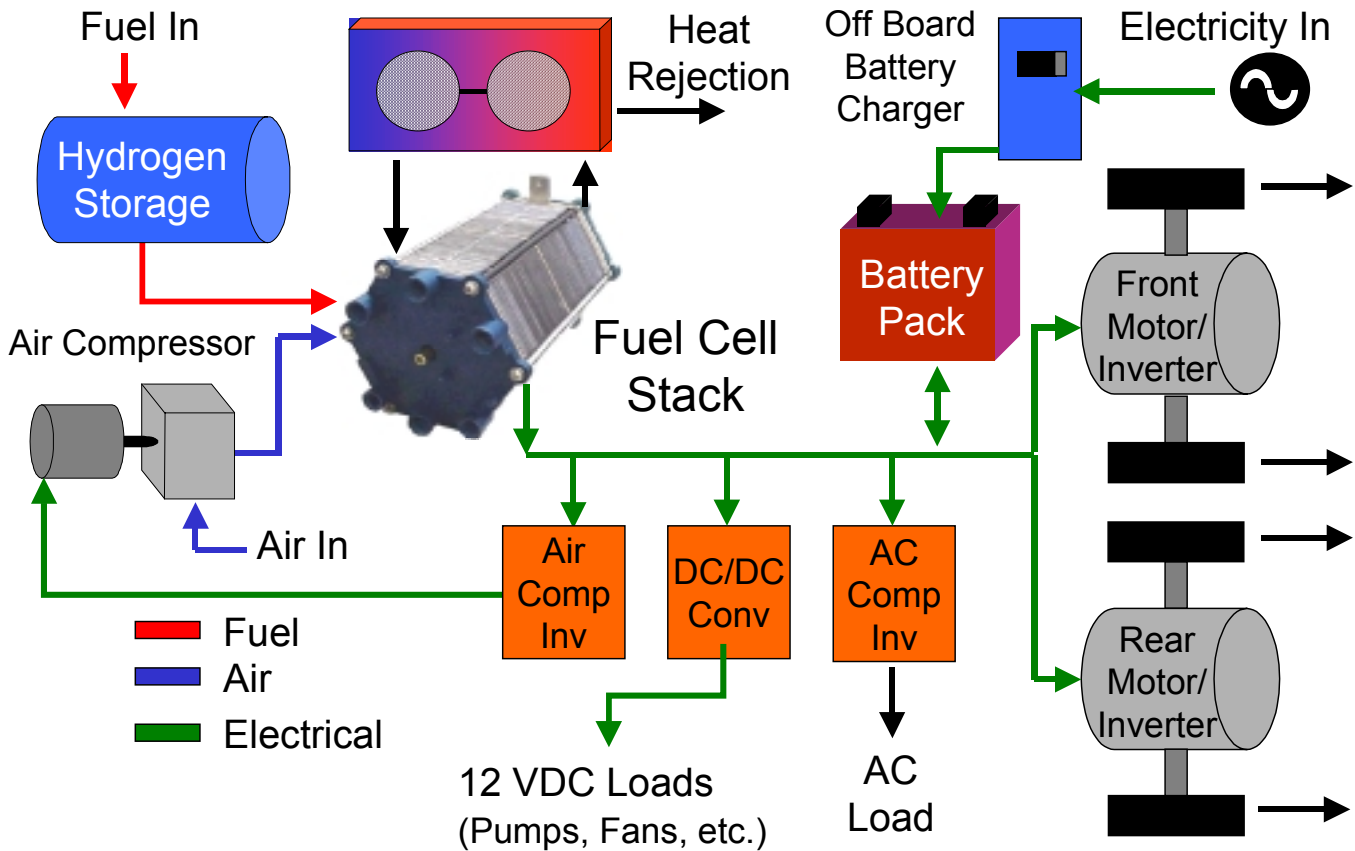
Figure 1. System Schematic of Fuel Cell Hybrid Electric Drivetrain Components

fuel storage, and range. Virginia Tech is currently developing a fuel cell hybrid Suburban for the FutureTruck competition sponsored by General Motors and the U.S. Dept. of Energy; See Patton et al. (2001) and Gurski et al. (2002) for more detailed information.

COMPONENT MODELS

ELETRIC DRIVETRAIN

A schematic of the components and energy flows for the overall vehicle model is shown in Fig. 1. The four-wheel electric traction drive consists of two, 83 kW AC induction motors to give the vehicle a total of 166 kW of tractive power. This power level is set to give the converted FCHEV acceleration, gradeability and towing performance similar to the stock vehicle (210 kW 5.3 l V8 engine). The motors have an integrated planetary gear reduction set that replaces the stock four-speed automatic transmission, and the vehicle is geared for a top seed of 130 kph (80 mph). The component model for the motor and inverter is based on a validated ADVISOR model (Senger et al., 1998).

FUEL CELL SYSTEM MODEL

The fuel cell system is based on measurements from a direct hydrogen 110 cell 20 kW gross system from Energy Partners (Fuchs et al., 2000). This system operates at a pressure of 1.7 atm at peak power using a twin screw compressor. An ADVISOR model of this system validated with measured hybrid fuel cell vehicle data is reported in Ogburn (2000) and Ogburn et al. (2000).

For this work, the fuel cell system is a constrained load following model with a minimum load, and the parasitic loads (air compressor drive and coolant pumps/fans) vary directly with fuel cell stack gross output power. The fuel cell model active area plus parasitic power are linearly scaled to generate the desired output power. A scaled 100 kW gross system characteristic is shown in Figure 2. The parasitic power represents about 24% of the gross stack power output at peak power. While this is not a particularly efficient system, it is based on measurements from currently available systems and components.
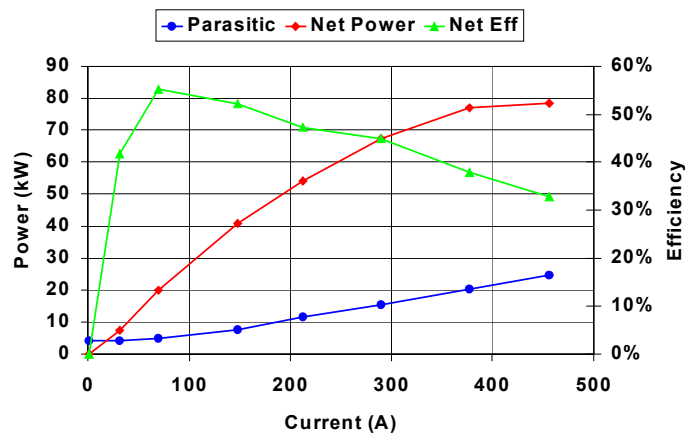
Figure 2. 100 kW gross Fuel Cell System Model

The fuel cell system model does not currently include any cold-start effects, either in the form of a fuel consumption or efficiency penalty, or in limited power output availability. Cold start issues are one of the reasons to hybridize a fuel cell vehicle.
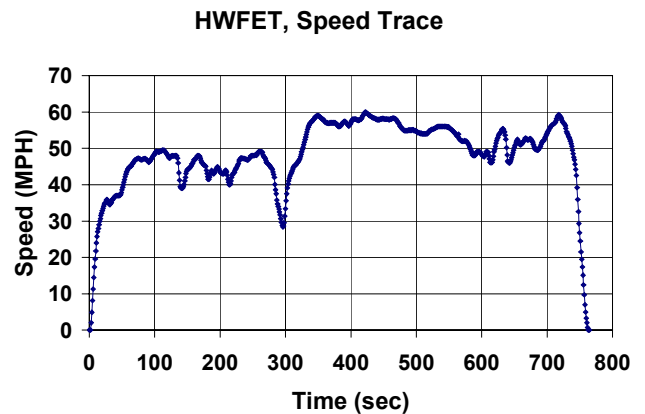
BATTERY MODEL

The battery model is based on a 25 Amp-hour (Ah) Hawker Genesis sealed lead acid battery. The capacity and charge/discharge internal resistance maps are linearly scaled to generate battery components with the desired characteristics. The nominal power available from the batteries is reported as the instantaneous power available at an average 60% state of charge (SOC). In all cases, twenty-eight, 12 V modules are used to match the vehicle nominal bus voltage for the electric drivetrain.

VEHICLE ADVISOR MODEL

The road load parameters from Table 1, the fixed electric drivetrain, and variable size fuel cell and battery components are implemented in an ADVISOR model of the FCHEV. A range of vehicle configurations using fuel cell component sizes from zero (a pure battery electric vehicle) up to a pure fuel cell vehicle (zero battery) are selected to investigate the degree of hybridization with fixed vehicle mass and thus performance. The power requirement for each configuration is determined by the drivetrain power and additional accessory loads. For this class of vehicle, the dual motor drivetrain requires an output of approximately 166 kW and accessory loads (power steering, power brakes, 12V loads) are set at 1.5 kW. Based on these power requirements, approximately 200 kW net from the combination of fuel cells and batteries is needed. The ability to supply a nominal 200 kW to the high voltage electrical bus of the vehicle ensures that the performance is limited by the drivetrain, and not the hybrid power system.

Figure 3 shows some example time series results for the highway driving cycle (top time trace) for a sample
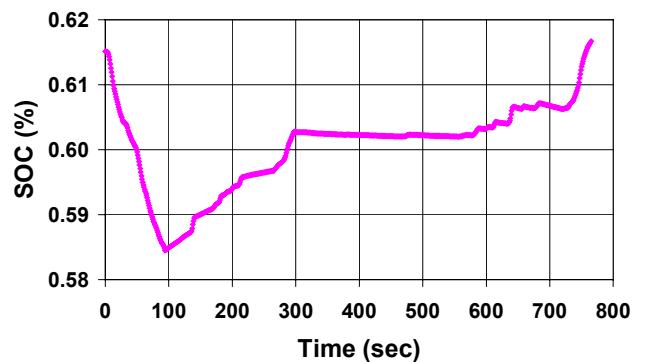
Figure 3. ADVISOR Model Results for a Highway Cycle

3

hybrid case. ADVISOR has the option to iterate for a zero net change in battery SOC over the cycle to provide consistent, SOC-corrected fuel economy results (no battery net energy contribution). The control strategy starts th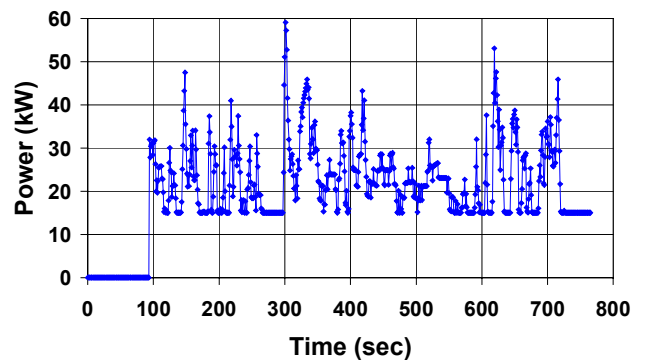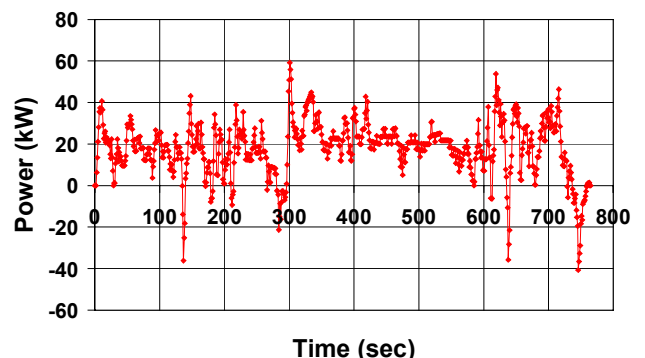e fuel cell system when the battery SOC reaches 40%. (Not shown is that the control strategy would shut the fuel cell system off at 80% battery SOC). The control strategy operates the fuel cell system at a minimum power level (15% of gross stack power, or 15 kW which ever is less) and is load following otherwise. For all of the hybrid results given below, zero net SOC change over a drive cycle and the same control strategy are used.

This simulation model is used to evaluate the fuel economy and component efficiencies for different combinations of fuel cell and battery size operating on four different drive cycles, as presented below.

DEGREE OF HYBRIDIZATION RESULTS

For simplification purposes, the choices of fuel cell and battery size are set to uniform increments of 10 kW and 2 Ah, respectively. The lower limit of fuel cell power is chosen to ensure that the vehicle is at least charge sustaining at a constant speed of 103 kph (65 mph) on a level road. Thus, the minimum *net* power required from the fuel cell system is approximately 30 kW. This sets the lower bound of hybrid configurations at 40 kW *gross* stack power. The configurations of hybrid vehicles cover the spectrum from this lower limit up to the maximum net fuel cell power of 181 kW for the pure fuel cell vehicle configuration. The remaining power not supplied by the fuel cell determines the size of battery needed for a hybrid configuration.

The degree of hybridization is indicated by the ratio of gross fuel cell power in a hybrid configuration to gross fuel cell power for the pure fuel cell configuration (240 kW). This factor is also close to the ratio of net fuel cell power to net fuel cell plus battery power (= 200 kW). Table 2 and Figure 4 lists the range of component sizes used to provide approximately constant performance.

Table 2. Hybrid Component Size Ratio

Ratio	Fuel Cell Gross kW	Fuel Cell Net kW	Battery Power kW	Battery Size Ah
0.00	0	0	262	105
0.17	40	30	175	72
0.21	50	38	165	68
0.25	60	45	157	65
0.29	70	53	150	62
0.33	80	60	140	58
0.38	90	68	130	54
0.42	100	75	125	52
0.46	110	83	116	48
0.50	120	90	105	44
0.54	130	98	95	40
0.58	140	105	87	36
0.62	150	113	78	32
0.67	160	120	68	28
0.71	170	128	60	25
0.75	180	135	53	22
0.79	190	143	44	18
0.83	200	150	33	14
0.88	210	158	29	12
0.91	220	166	20	8
0.96	230	173	9	4
1.00	240	181	0	0
1.21	240	181	40	16
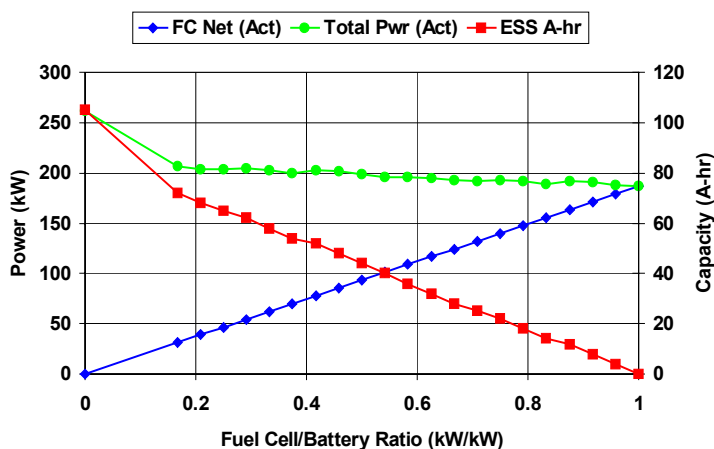
Figure 4. Component Sizes for Equal Performance
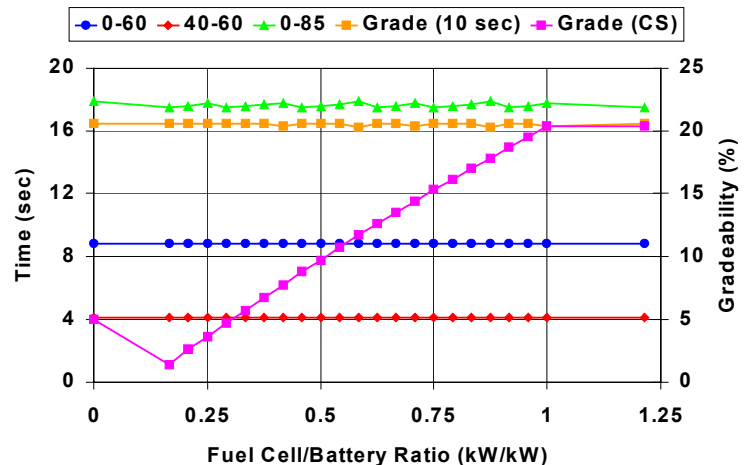
Figure 5. Performance and Gradeability

For each vehicle case, the battery size is adjusted until there is just enough power available to supplement the fuel cell power to achieve performance equal to the pure fuel cell case (Fig. 5). One additional case is investigated where a battery pack (sized to capture most of the available regenerative brake energy) is added to the pure fuel cell stack size resulting in a degree of hybridization of 1.21.

Each vehicle also has consistent instantaneous gradeability of about 20 % at 88 kph (55 mph). For very long grades, the charge-sustaining (CS) gradeability depends on fuel cell output only, with no depletion of the battery. The continuous gradeabilty shown in Fig. 5 increases linearly with fuel cell size as expected. A degree of hybridization of greater than 0.33 (80 kW gross fuel cell stack power) is required for a charge-sustaining gradeability of 6 %.

The unadjusted, gasoline equivalent energy fuel economy (mpgge) results are presented in Figure 6. Four standard drive cycles of varying dynamics are investigated; the Urban Dynamometer Driving Schedule (UDDS or City cycle), the Highway Fuel Economy Test (HWFET or Highway cycle), the aggressive driving part of the Supplemental FTP Test (US06 cycle), and a constant highway speed of 103 kph (65 mph) on a level road (C65). The two non-hybrid, limiting cases are described first.

PURE BATTERY ELECTRIC VEHICLE

The pure electric vehicle (EV) model is used as a reference limiting case. Since the primary assumption in selecting the battery size is power available to meet the performance requirements, the range of this type of vehicle would probably not be practical using a lead-acid battery pack. The capacity of the battery pack is sized at 105 Ah to provide 262 kW of instantaneous power at 60% state of charge (SOC). The resulting range for this vehicle is about 115 km (70 miles) at a constant speed of 103 kph (65 mph), or less than 90 km (55 miles) on repeated US06 cycles. The latter result probably gives a better indication of the real-world range for this battery-only electric vehicle.

The pure EV fuel economy results have a factor of 0.3 applied to account for power plant generation, plus wall-charger and battery charge efficiencies to convert energy use from the vehicle bus to miles per gallon of gasoline equivalent (mpgge) (Wang, 1999). The results from the ADVISOR simulations show fuel economy comparable to, but lower than the hybrid vehicles. The obvious disadvantage for this class vehicle is the limited EV range.

PURE FUEL CELL VEHICLE

The other limiting case is a pure fuel cell vehicle with no battery storage. In keeping with the assumption that all

vehicles should have a fixed drivetrain and the same performance, the pure fuel cell vehicle provides 181 kW net power. This power is enough to provide the 166 kW drivetrain and 1.5 kW accessory loads. The same fuel cell model is used in each vehicle. For this non-hybrid pure fuel cell model, a 240 kW gross power stack is selected, and the control strategy allows the system to operate at very low net power output (1 %). As shown in Fig. 6, this vehicle model produced lower fuel economy than any of the hybrid cases, except on the non-dynamic C65 drive cycle.

Since the vehicle has no energy storage capability, the regenerative energy available from deceleration cannot be captured. To see how much effect this has on fuel economy, a similar 240 kW model was run with a small 16 Ah capacity battery pack sized to capture most of the regenerative braking energy on the US06 cycle. This model produced fuel economy better than the pure fuel cell case (as expected), but not as good as some of the smaller fuel cell hybrid cases for reasons discussed below.

HYBRID FUEL CELL/BATTERY VEHICLES

The choices for the hybrid fuel cell vehicle component configurations are governed by the peak power requirement . Along with the fixed total mass and fixed drivetrain configuration, this method ensures that all hybrid configurations perform similarly, as demonstrated in Fig. 5. Consistent performance across all hybrid configurations ensures that variations in fuel economy are simply a result of fuel cell and battery size combinations, or degree of hybridization.

Hybrid Fuel Economy Results

The degree of hybridization fuel economy results shown in Fig. 6 depend on the dynamics of the drive cycle. For the constant highway speed cycle (C65), the initial increase is due to the increase in stack size and efficiency, then the fuel economy is relatively constant. The constant power required is always above the fuel cell minimum power criteria, so the control strategy does not play much of a role. There is no regenerative brake energy, so the battery size does not affect the results significantly.

The more dynamic drive cycles all show a more complex interaction with degree of hybridization. The fuel economy rises somewhat with fuel cell size, then remains relatively constant or decreases before rising and dropping off again. The initial rise is from the increase in fuel cell size and efficiency as for the C65 case. As the fuel cell size continues to increase and the battery capacity decreases, the interaction between the power spectrum of the drive cycle, the minimum fuel cell power and the energy processed through the battery produces the peaks in fuel economy around degrees of hybridization of 0.3 - 0.5.
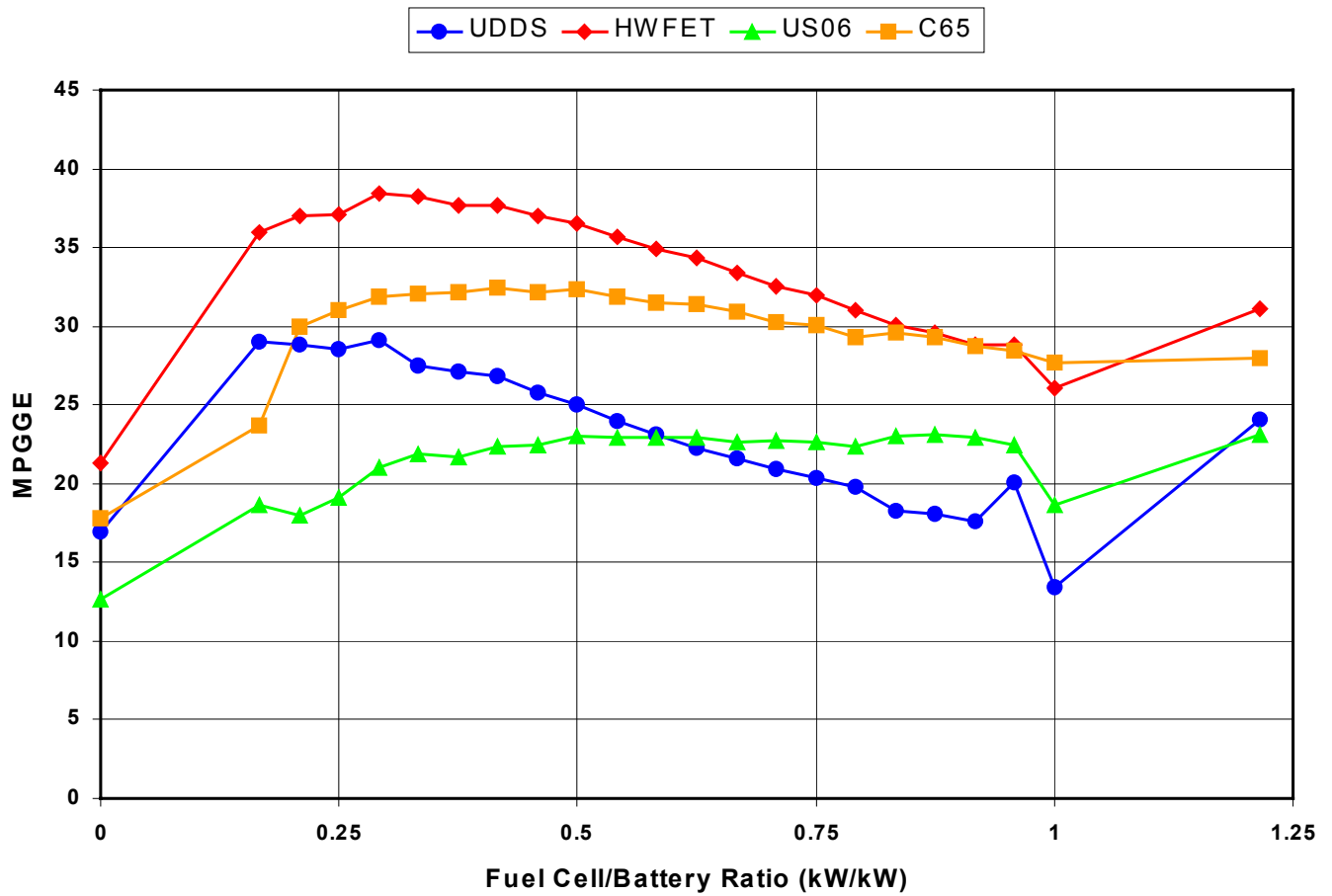
Figure 6. Fuel Economy Results for Degree of Hybridization
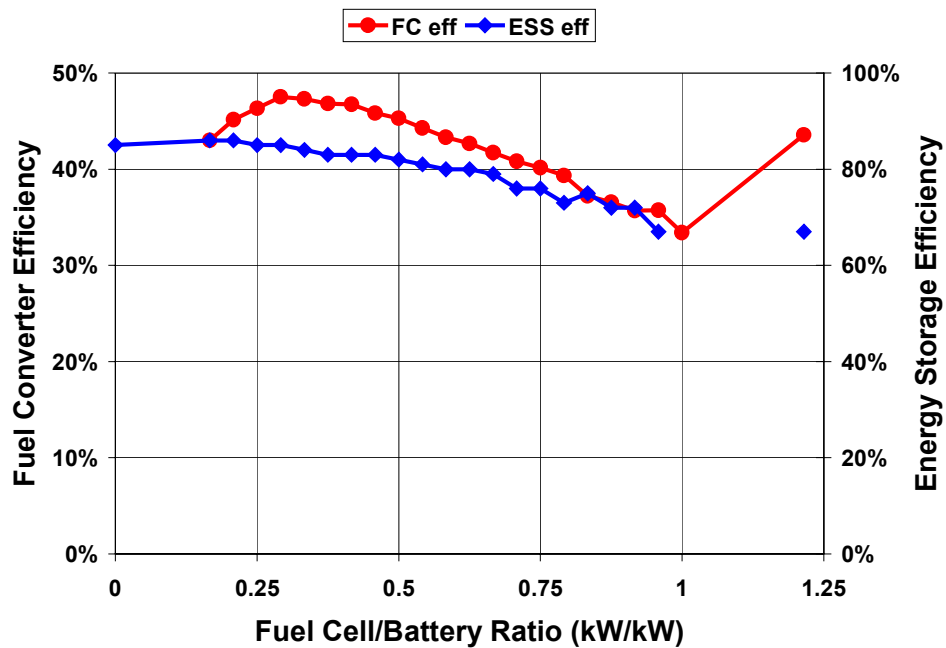
Figure 7. HWFET Component Efficiency Variation with Degree of Hybridization

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To help illustrate these interactions, Fig. 7 shows the HWFET cycle overall efficiency of the battery and fuel cell systems as the degree of hybridization varies. The peak in Highway fuel economy occurs where the fuel cell efficiency is highest. Figure 8 shows a sample of the Highway fuel cell power spectrum (kW-hr expended at a particular power level) along with the fuel cell net system part-load efficiency. For this 100 kW size fuel cell, a large fraction of the energy conversion occurs at the minimum fuel cell power level enforced by the control strategy. The choice of this minimum power level is evident in this figure – the fuel cell system efficiency drops off rapidly below this power. However, when the system is forced to cycle on and off to maintain this minimum power level, more energy must be processed through the round-trip charge/discharge penalty of the battery system. The fuel cell system model does not currently use any penalty for start-up and shutdown, but these losses are expected to be small if the system is already in a warmed-up state .

As the degree of hybridization increases, not only does the minimum power level increase with stack size, but the increased total energy processed through the smaller and small battery capacity leads to lower cycle average battery efficiency. Some of the decrease in fuel economy for high degrees of hybridization is also due to reduced ability to capture regenerative brake energy as the battery capacity shrinks.

Figure 9 shows the fuel cell power spectrum for the pure fuel cell vehicle case. Since there is no energy storage, the large fuel cell must operate at very low power levels most of the time on the Highway cycle. This lowers the average fuel conversion efficiency and fuel economy. Operation of a PEM fuel cell at low load can also have detrimental effects on water management, as discussed in Kulp and Nelson (2001). The US06 cycle shows little decrease in fuel economy as stack size increases due the much higher power demands.

For the fixed fuel cell and battery technology considered here (by scaling), the fuel cell size can have a 50% impact on fuel economy. The results do not show a single degree of hybridization that is best for all drive cycles. The control strategy and minimum power may have a significant impact on these results. Other considerations may also dictate a minimum fuel cell size, such as towing performance.

TOWING PERFORMANCE

The goals of reducing or eliminating vehicle emissions while increasing energy efficiency of vehicles should not sacrifice any of the vehicle performance capabilities. One aspect of sport utility vehicle design is towing characteristics. Analyzing a vehicle while towing a heavy trailer offers a look at sustained high power driving cycles. The towing cycles considered here consist of constant speeds of 88, 80, and 72 kmh (55, 50, and 45

mph) on a constant grade of 5%. The vehicle simulation starts at the cycle speed, so there is no acceleration at the beginning of the cycle. For these cases, the vehicle is equipped with a 3000 kg (6600 lb) trailer, to give a gross combined vehicle weight of 5900 kg (13,000 lb). This weight is similar to the gross combined towing weight rating of some drivetrain configurations of a production Suburban. Because the vehicle is a hybrid, and constant mass, power and performance are assumed, some hybrid configurations are charge-depleting (battery SOC is reduced) with a finite driving range. There is a finite amount of power required by the towing cycle at each speed. Once the fuel cell system net power can meet this power level, the vehicle is charge sustaining at that speed and the range is limited by fuel rather than battery power and SOC. These results suggest that a degree of hybridization greater than 60% (140 kW gross stack power) should provide good towing performance, but at the expense of some decrease in fuel economy. The sizing of an engine for towing in a conventional vehicle has a similar penalty.

CONCLUSIONS

The results presented isolate the effect of fuel cell size on vehicle fuel economy for a wide range of degree of hybridization. The constraints imposed on the current results are:

- Fixed total vehicle mass
- Fixed electric traction drive
- Fixed vehicle performance (as a result of above)
- Nominal net power from fuel cell plus battery
- Fixed component technology, scaled in size/power
- Compressed hydrogen fuel
- No cold-start effects considered.

The fuel economy results demonstrate that the degree of hybridization can improve energy efficiency by as much as 50%. As expected, some battery storage allows for capture of regenerative brake energy (significant for this vehicle mass). The results also show that the control strategy for minimum fuel cell power, the power spectrum of the drive cycle, and the fuel cell and battery efficiency interact in a somewhat complex way. For the fuel cell system technology considered here, the low-load system efficiency depends on the air compressor power and minimum air compressor speed, and the control strategy for minimum fuel cell power, and battery size relative to the energy storage demand. For this class of large SUV, depending on the factors above, the fuel cell system benefits from downsizing somewhat to prevent excessive operation at light load or on/off operation due to minimum power requirements. A clear optimum fuel cell size does not appear that is independent of the drive cycles considered, however a degree of hybridization in the range of 30-50% appears to be a good compromise. Towing requirements may dictate a larger fuel cell stack size to maintain charge sustaining operation on a long grade.
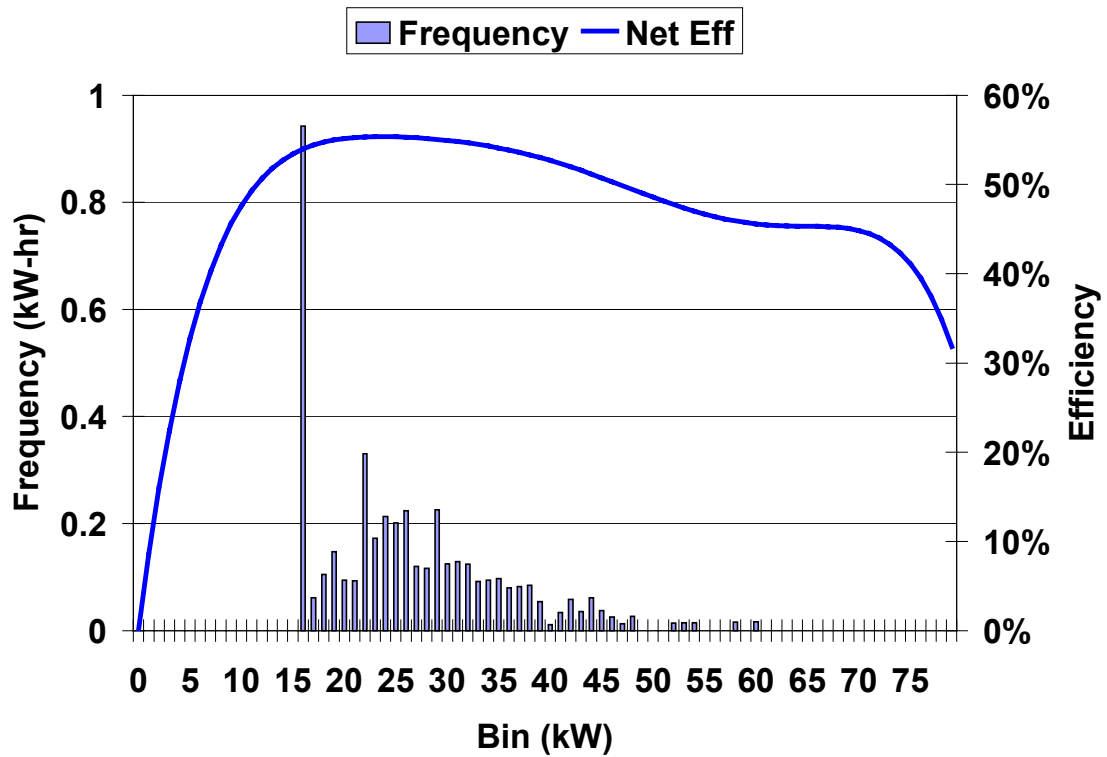
Figure 8. 100 kW Hybrid Fuel Cell Power Spectrum and Part-Load Net System Efficiency
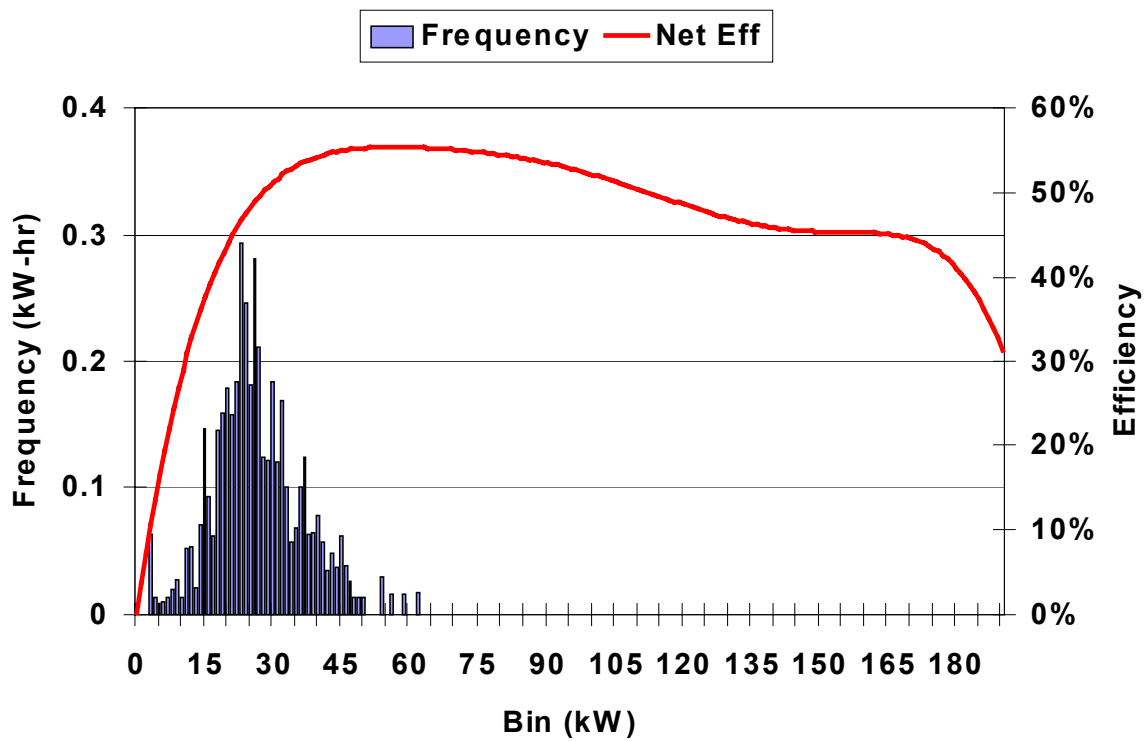
Figure 9. Pure Fuel Cell Power Spectrum and Part-Load Net System Efficiency

Future work will consider cold-start effects, fuel cell and battery technology/efficiency, and control strategy impact. The fuel cell and battery components are sized to meet the performance requirements in this work. In Wipke et al. (2001), the components are constrained to meet the performance requirements, but then the components sizes and control strategy are optimized for fuel economy. Wipke et al. (2001) also found that the drive cycle influences the fuel cell size for best fuel economy.

Note: This revised paper is based on the paper by Atwood, et al. (2001), with revised and corrected results to reflect consistent warm-start conditions with control strategy modifications.

ACKNOWLEDGMENTS

REFERENCES

P. Atwood, S. Gurski, D. J. Nelson, and K. B. Wipke (2001), " Degree of Hybridization Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle," SAE Paper 2001-01-0236, in Fuel Cell Power for Transportation 2001, SP-1589, pp. 23-30.

D. J. Friedman (1999), "Maximizing Direct-Hydrogen PEM Fuel Cell Vehicle Efficiency – Is Hybridization Necessary?," SAE paper 1999-01-0530, SP-1425, pp. 9-17.

D. J. Friedman, T. Lipman, A.. Eggert, S. Ramaswamy, and K. Hauer (2000), "Hybridization: Cost and Efficiency Comparisons for PEM Fuel Cell Vehicles," SAE paper 2000-01-3078, SP-1557, pp. 1-12.

M. Fuchs, F. Barbir, A. Husar and J. Neutzler, D. J. Nelson, M. J. Ogburn, and P. Bryan (2000), "Performance of an Automotive Fuel Cell Stack," VA, SAE paper 2000-01-1529, 5 pgs.

S. Gurski, D. Evans, D. Knox, M. Conover, A. Harris, H. Lohse-Busch, S. Kraft, Douglas J. Nelson, (2002), "Design and Development of the 2001 Virginia Tech FutureTruck: A Fuel Cell Hybrid Electric Vehicle," to be published by SAE, 18 pages.

G. Kulp and D.J. Nelson (2001), "A Comparison of Two Fuel Cell Air Compression Systems at Low Load", SAE Paper 2001-01-2547, Proceedings of the 2001 SAE Future Transportation Technology Conference, Costa Mesa, Ca.

W. Luttrell, B. King, S. Postle, R. Fahrenkrog, M. Ogburn, D. J. Nelson (1999), "Fuel Cell System Efficiency in the Virginia Tech 1999 Hybrid Electric FutureCar," 1999 Environmental and Advanced Technology Vehicles Conf. & Exposition, June 13-16, 1999, Ypsilanti, MI, published by SAE/ESD on CD-Rom.

M. A. Merkle, R. D. Senger, and D. J. Nelson (1997), "Measured Electric Vehicle Drivetrain Efficiencies for the Virginia Tech FutureCar," Presented at the 1997 SAE Intl. Congress, Detroit, MI, Feb. 24-27.

M. J. Ogburn (2000), "Systems Integration, Modeling and Validation of a Fuel Cell Hybrid Electric Vehicle," MSME Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, June, 2000; available online http://scholar.lib.vt.edu/theses/available/etd-05032000-15510004/unrestricted/ .

M. J. Ogburn, D. J. Nelson, K. Wipke, and T. Markel (2000), "Modeling and Validation of a Fuel Cell Hybrid Vehicle," Proceedings of the 2000 Future Car Congress, April 2-6, Arlington, VA, SAE paper 2000-01-1566, 13 pgs.

M. J. Ogburn and D. J. Nelson (2000), "Systems Integration and Performance Issues in a Fuel Cell Hybrid Electric Vehicle," SAE Paper 2000-01-0376, in Fuel Cell Power for Transportation 2000, SP-1505, pp. 125 - 137.

D. Patton, J. Latore, M. J. Ogburn, S. Gurski, P. Bryan, and D. J. Nelson (2001), "Design and Development of the 2000 Virginia Tech Fuel Cell Hybrid Electric FutureTruck", SAE SP-1617, 18 pgs.

R. D. Senger, M. A. Merkle, and D. J. Nelson (1998), "Validation of ADVISOR as a Simulation Tool for a Series Hybrid Electric Vehicle," SAE Paper 981133, Technology for Electric and Hybrid Vehicles, SP-1331, pp. 95-115.

M. Q. Wang (1999), GREET 1.5 - Transportation Fuel Cycles Model: Methodology, Development, Use, and Results, Center for Transportation Research, Argonne National Laboratory, ANL/ESD-39, Vol. 1, Argonne, Ill.

Wipke, K., T. Markel, and D. Nelson (2001), "Optimizing Energy Management Strategy and Degree of Hybridization for a Hydrogen Fuel Cell SUV," accepted for publication at 18th Electric Vehicle Symposium (EVS-18), Berlin, Germany, October 20-24, 2001

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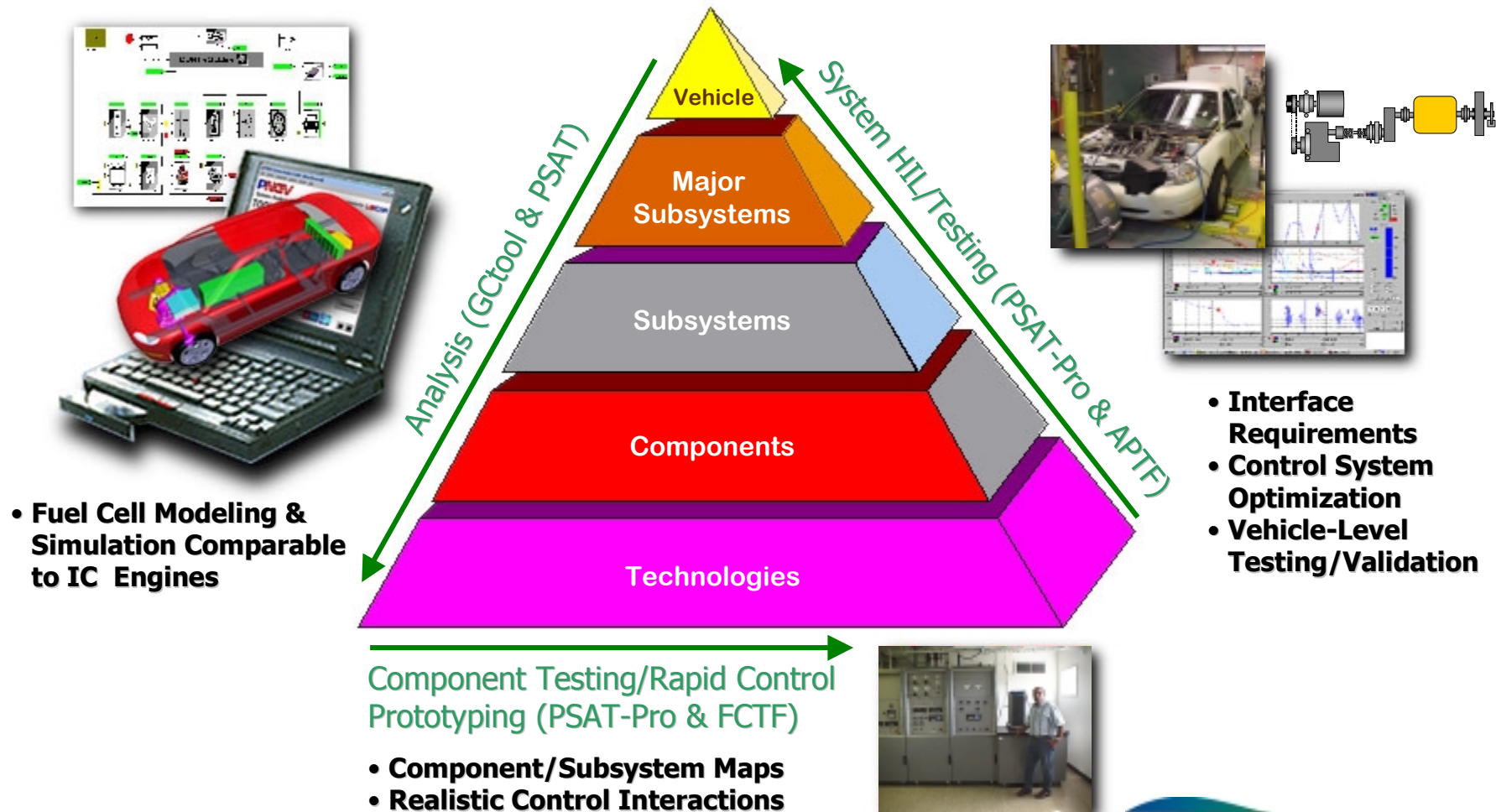(540) 231-4324 Doug.Nelson@vt.edu

Fuel Cell Vehicle System Analysis

R. K. Ahluwalia, H. K. Geyer, K. Hardy, A. Rousseau

ADVISOR/PSAT Users Conference
USCAR
August 28-29, 2001

TRANSPORTATION
TECHNOLOGY R&D CENTER
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Streamlined FC Development

Analysis (GCtool & PSAT)

System HIL/Testing (PSAT-Pro & APTF)

Pyramid levels (top to bottom):
- Vehicle
- Major Subsystems
- Subsystems
- Components
- Technologies

- **Fuel Cell Modeling & Simulation Comparable to IC Engines**

- **Interface Requirements**
- **Control System Optimization**
- **Vehicle-Level Testing/Validation**

Component Testing/Rapid Control Prototyping (PSAT-Pro & FCTF)

- **Component/Subsystem Maps**
- **Realistic Control Interactions**

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GCtool

- **Fuel cell systems analysis tool funded by DOE-OAAT (Energy Conversion)**
  - PEFC, SOFC, PAFC, MCFC
  - Fuels: H2, CH4, CH3OH, C8H18, diesel, gasoline
- **GCtool has been used to generate steady-state look-up tables for fixed system configurations**

PSAT & PSAT-Pro

- **Hybrid vehicle simulation code funded by DOE-OAAT (Vehicle Systems)**
  - "Forward" (driver-to-wheels) model – detailed models with realistic control and transient behavior

- **PSAT-Pro: Subsystem/system control code**
  - PSAT models plus control features and hardware operational safeguards
  - Enables consistent rapid control prototyping, hardware-in-the-loop and vehicle control system integration

Fuel Cell Test Facility
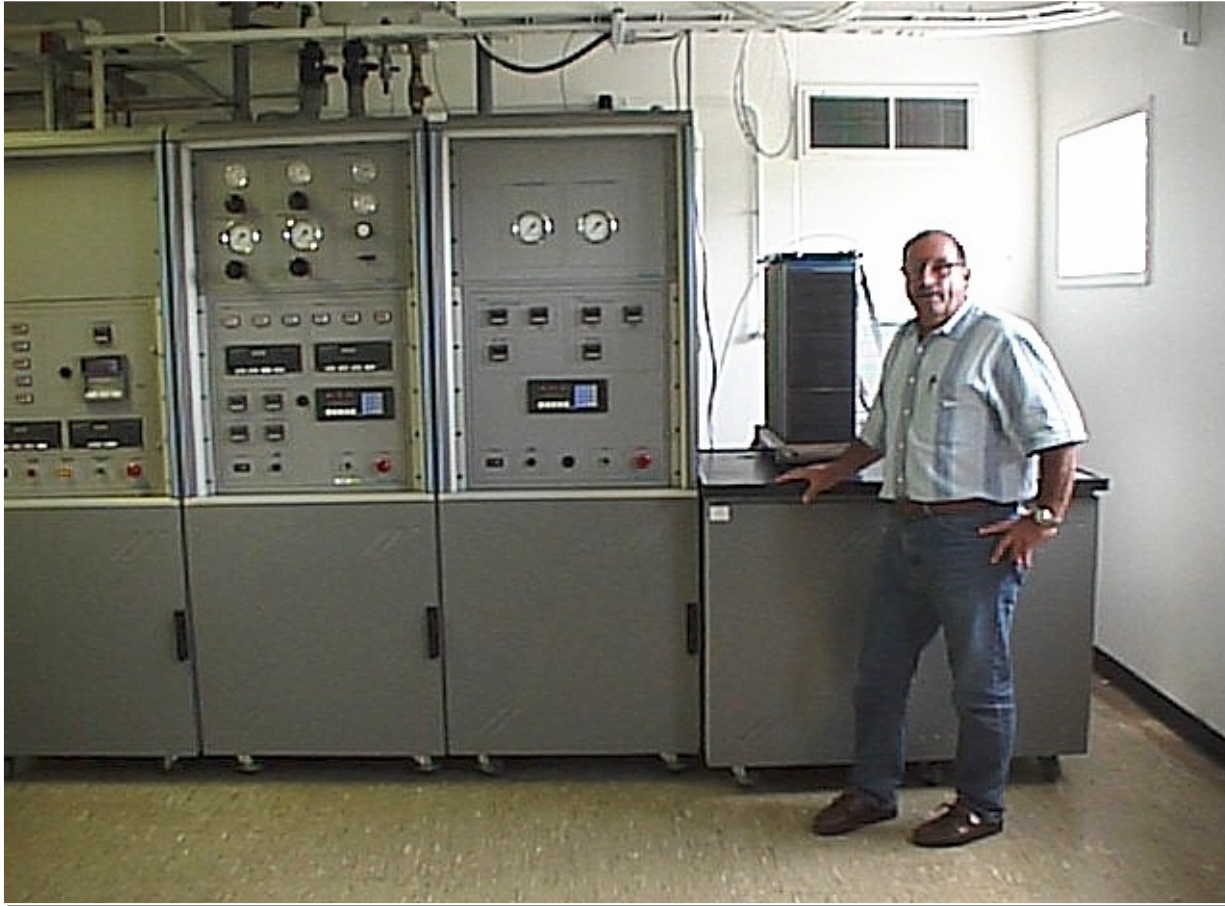
- Gas mixer
- Test station
- Humidifier
- Multi-fuel capability
- PSAT-Pro control unit installation (TBD)

Advanced Propulsion Test Facility

- Component, 2WD and 4WD Dynamometers

- SULEV and Transient Emissions Measurement

4WD CHASSIS DYNAMOMETER

2WD CHASSIS DYNAMOMETER

VEHICLE LIFT

DYNAMOMETER #4

LASER PARTICULATE ANALYZER ROOM

EMISSIONS BENCH

DYNO #2

DYNAMOMETER #1

CLIMATE CONTROL

DYNAMOMETER #3

CONTROL ROOM

ABC-150

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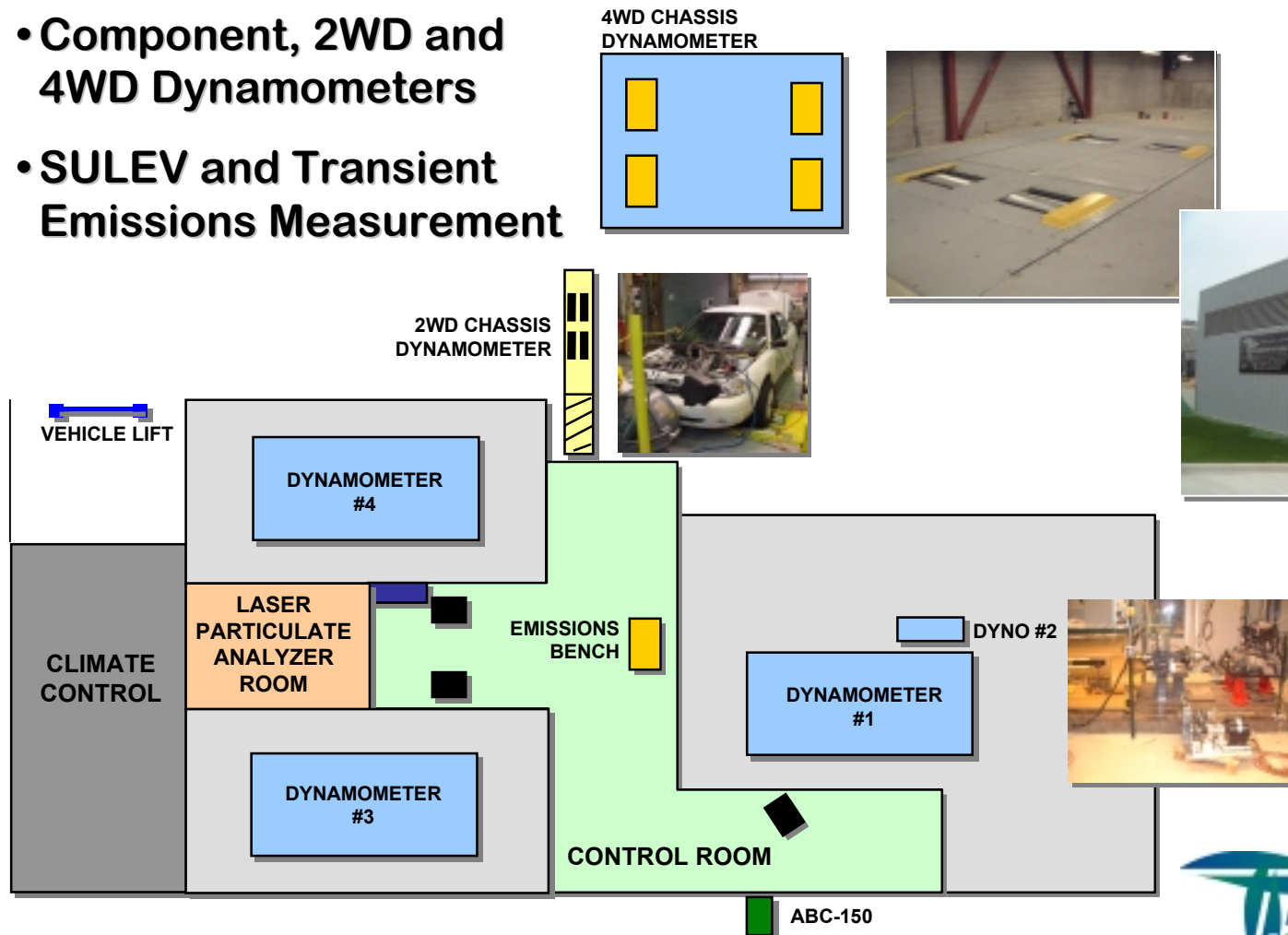
Modeling Approach

- **Develop engineering models of FC systems using GCtool architecture and link them to PSAT:**
  - *SPEED:* GCtool models are too detailed for fast transient analysis required for realistic vehicle simulation.
  - *APPLICATION:* GCtool focuses on component design and optimum subsystem configuration while PSAT requires maps or equations of subsystem behavior to predict system performance.

- **Detailed information is not available for building mechanistic models.**

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Engineering Model

- **Solves conservation equations for energy, mass, species and momentum with the source terms obtained from performance maps.**
  - ATR: Composition (P, T, GHSV, A/F, W/F)
  - WGS: CO Conversion (P, T, GHSV, CO_{in}, H_2O/CO)
  - PROX: CO/H_2 Conversion (P, T, GHSV, CO_{in}, O_2/CO)
  - PEFC: V(P, T, I, CO, AB)
  - Performance maps are design specific and become part of the data library.
  - Models are transient, can be multi-nodal and may directly interact with other components.

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PSAT Linkage

GCtool-ENG: FC system configuration
- Flexibility in arranging components.
- Some existing models can be modified.
- Utilities for math functions and gas properties.

MATLAB: Transient FC system model
- Translator writes executable from GCtool driver.
- Specific for each configuration.

PSAT/PSAT-Pro: Transient FC evaluation
- Executables in library.

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Status and Next Steps

- **Transient models being developed using GCtool.**
  - GCtool-ENG module completed.
  - Initial (limited) set of component maps from GCtool models.

- **Translator demonstrated.**

- **Initial focus on H_2-fueled FC.**
  - Comparison of configurations and control algorithms.
  - Optimization

- **FCTF being commissioned for testing components, subsystems and systems.**
  - Installation of PSAT-Pro control unit TBD.

2001 ADVISOR/PSAT User Conference

Wednesday
Special Presentation

ADVISOR 3.2 Overview and Demonstration

Tony Markel, National Renewable Energy Laboratory

Outline

- What's new in ADVISOR v3.2
- Demonstration of new features
- User statistics
- How we use the tool
- Things to look for in future versions

What's New in ADVISOR v3.2

- [What's New](#) web page
- Two resistor-three capacitor battery model
- Template scripts for linking to optimization tools
- Fuzzy logic controller for parallel hybrid based on OSU FutureCar and FutureTruck entries
- Revised Honda Insight control strategy
- Cycle varying accessory loads and vehicle cargo mass
- More robust data file update routines
- and more ...

Cycle Varying Accessory Loads
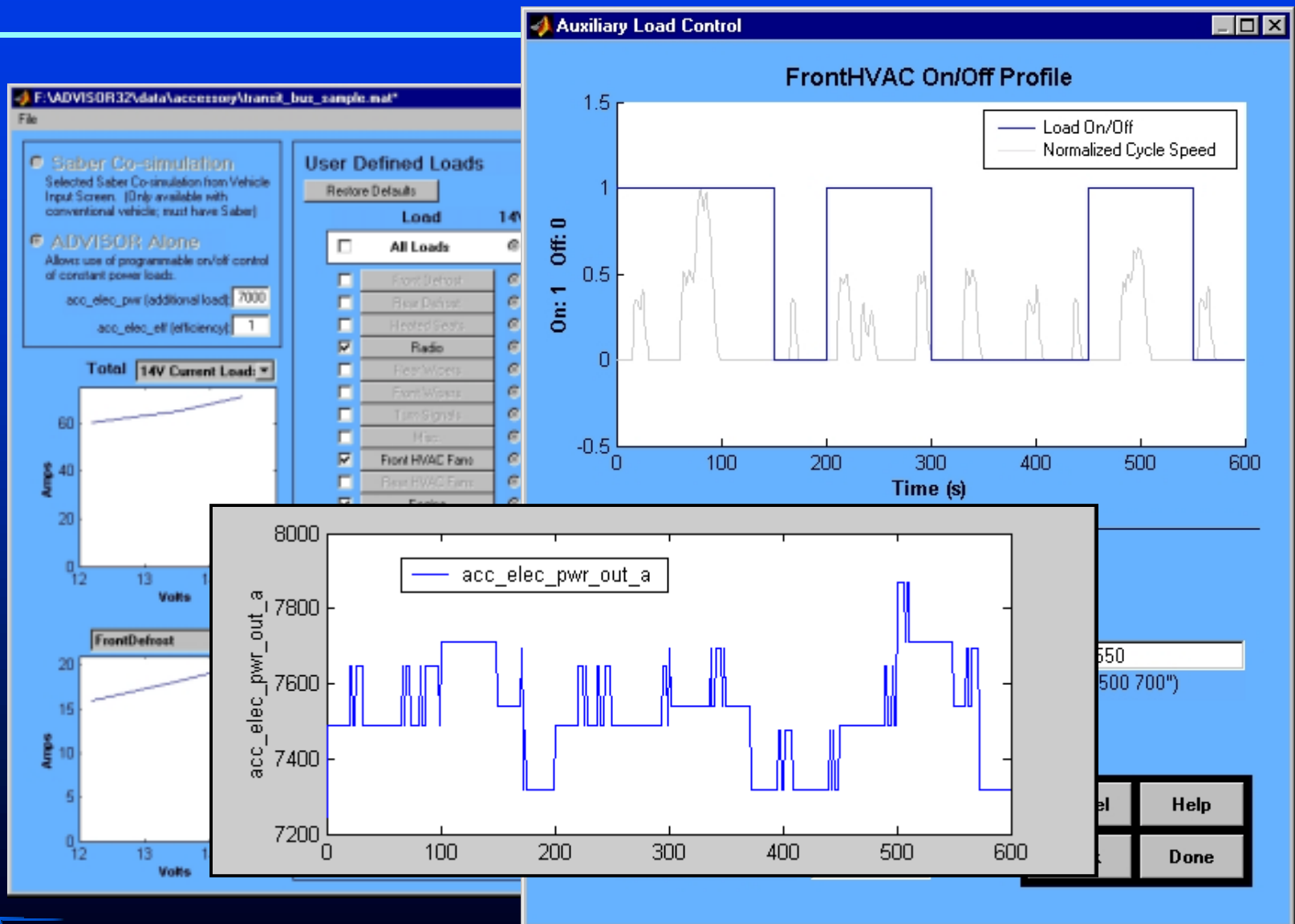
Two Resistor-Three Capacitor Battery Model

- Developed based on work with Saft
- Model development details presented at EVS-17
- Improves voltage calculation and power delivery capability

Battery Model

Terminals

Re =f(T, SOC)

Rt=f(T, SOC)

Rc =f(T, SOC)

Cb=f(T)

Cc=f(T)

Power request limited by Vmax, Vmin
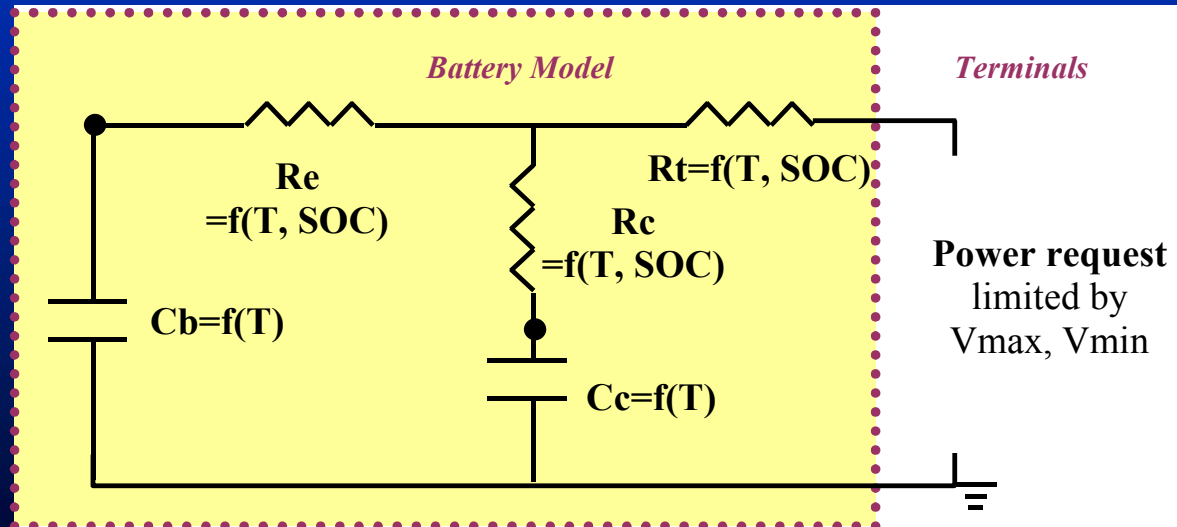
Optimization Tool Linkages

- Template files provided for linking ADVISOR with
  - VisualDOC
  - DIRECT
  - MATLAB Optimization Toolbox
  - iSIGHT
- Uses "GUI-free" functionality of ADVISOR
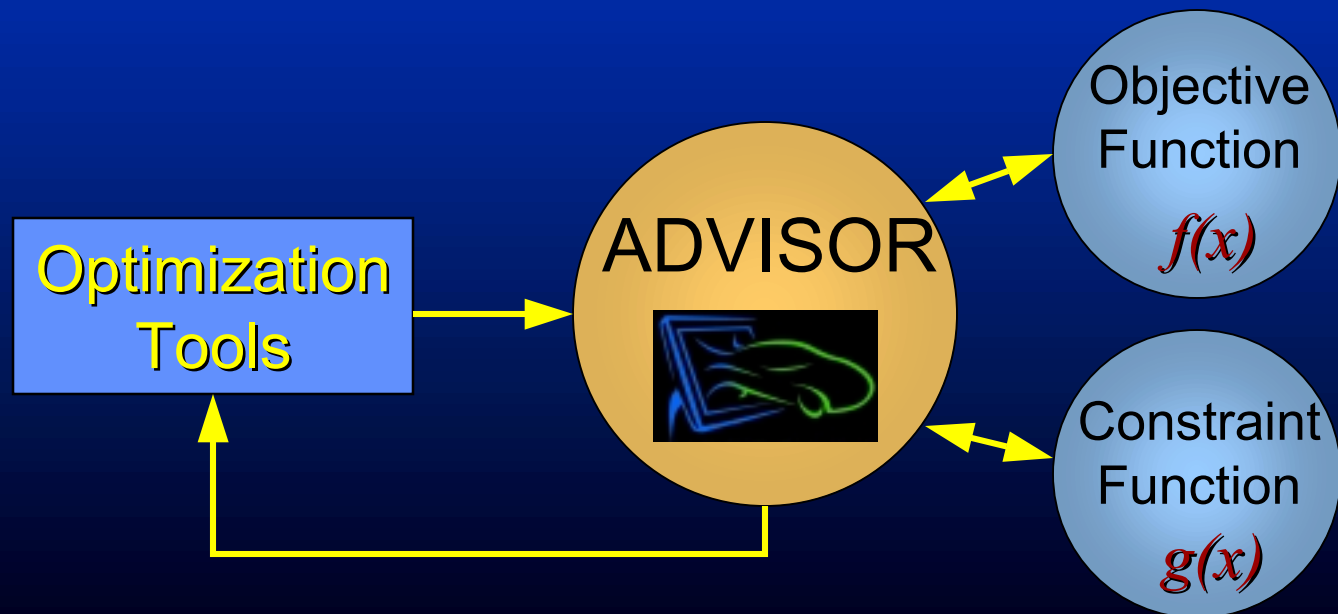
Revised Honda Insight Control Strategy
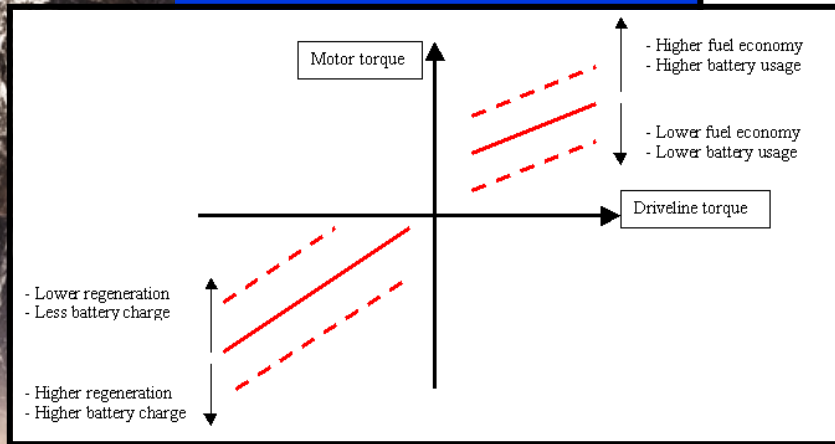
Based on test data, control strategy is not SOC dependent under normal operating conditions
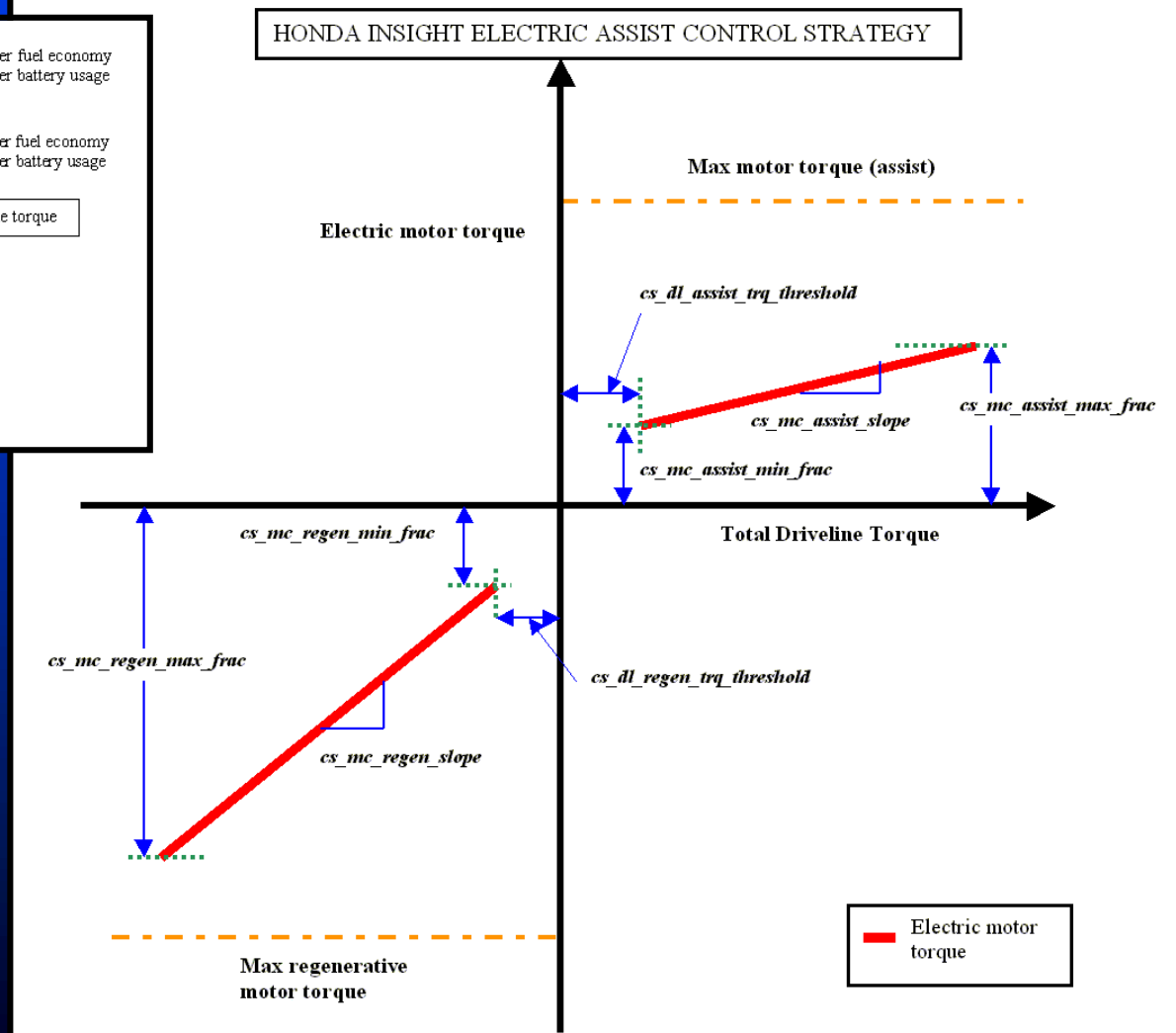
Fuzzy Logic Controller for Parallel Hybrid Vehicles From OSU

- Fuzzy logic control used in both FutureCar and FutureTruck entries by OSU
- Fuel Efficiency and Fuel Use Modes

Demonstration of new features

User Statistics

ADVISOR Downloads by Type of Organization

Legend:
- ☐ Industry
- ☐ Academia
- ☐ Government/Research

4%

45%

51%
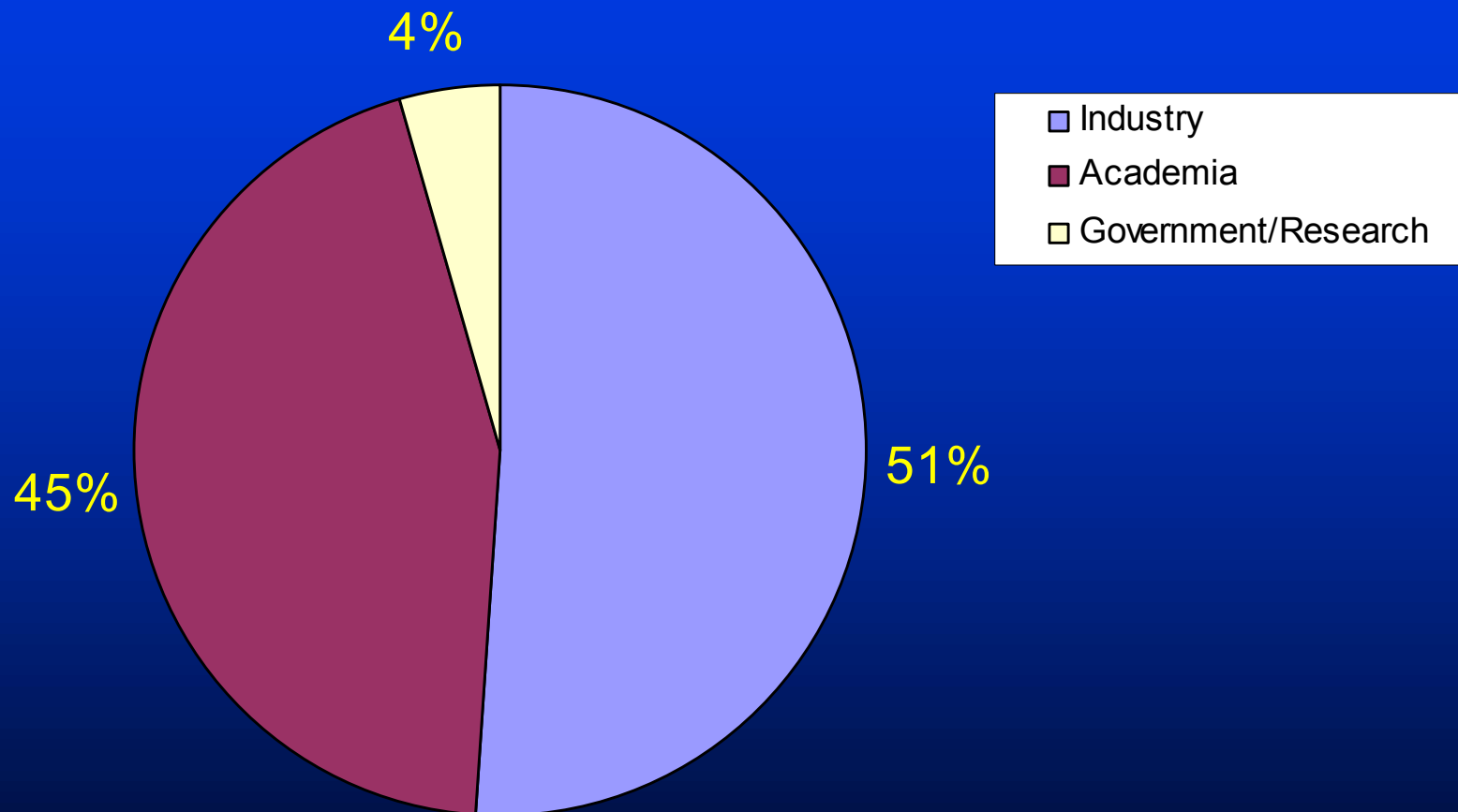
Industry is using ADVISOR

Legend includes organizations with 8 or more users

Legend:
- Ford Motor Company
- DaimlerChrysler Corporation
- General Motors
- Visteon
- Delphi
- Volvo
- Hyundai Motor Company
- Hitachi Ltd.
- Eaton Corporation
- Siemens Automotive Systems
- Fiat
- Honda
- Mathworks
- Ricardo, Inc.
- FEV Engine Technology
- Nissan Motor Company
- AVL
- Toyota Motor Corporation
- Robert Bosch
- Parametric Technologies Corp.
- TNO Automotive
- Mitsubishi Motors Corporation

Pie chart values: 70, 55, 39, 57, 21, 19, 18, 16, 15, 15, 15, 15, 14, 14, 13, 12, 12, 11, 9, 9, 8, 8, 8

As of 9/4/01

NREL, CENTER FOR TRANSPORTATION TECHNOLOGIES AND SYSTEMS

ADVISOR Users in Academia
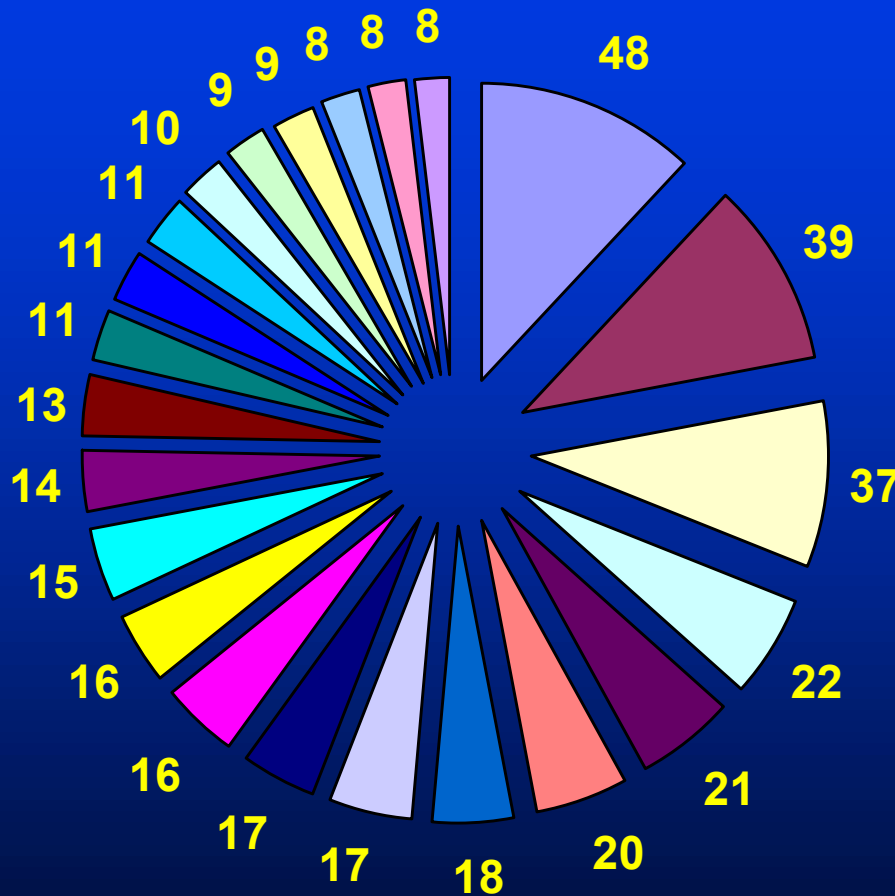
Legend:
- University of Michigan
- Ohio State University
- University of Maryland
- Texas A&M University
- University of California - Davis
- Texas Tech University
- University of Tennessee
- Georgia Institute of Technology
- Virginia Tech
- University of Bath
- George Washington University
- Pennsylvania State University
- National Tsing-Hua University
- Massachusetts Institute of Tech.
- Cornell University
- Seoul National University
- University of Oxford
- Kettering University
- West Virginia University
- Wayne State University
- Hanyang University
- Purdue University
- University of Windsor

Legend includes organizations with 8 or more users

As of 9/4/01

NREL, Center for Transportation Technologies and Systems

Cumulative ADVISOR Downloads and Version Release Dates
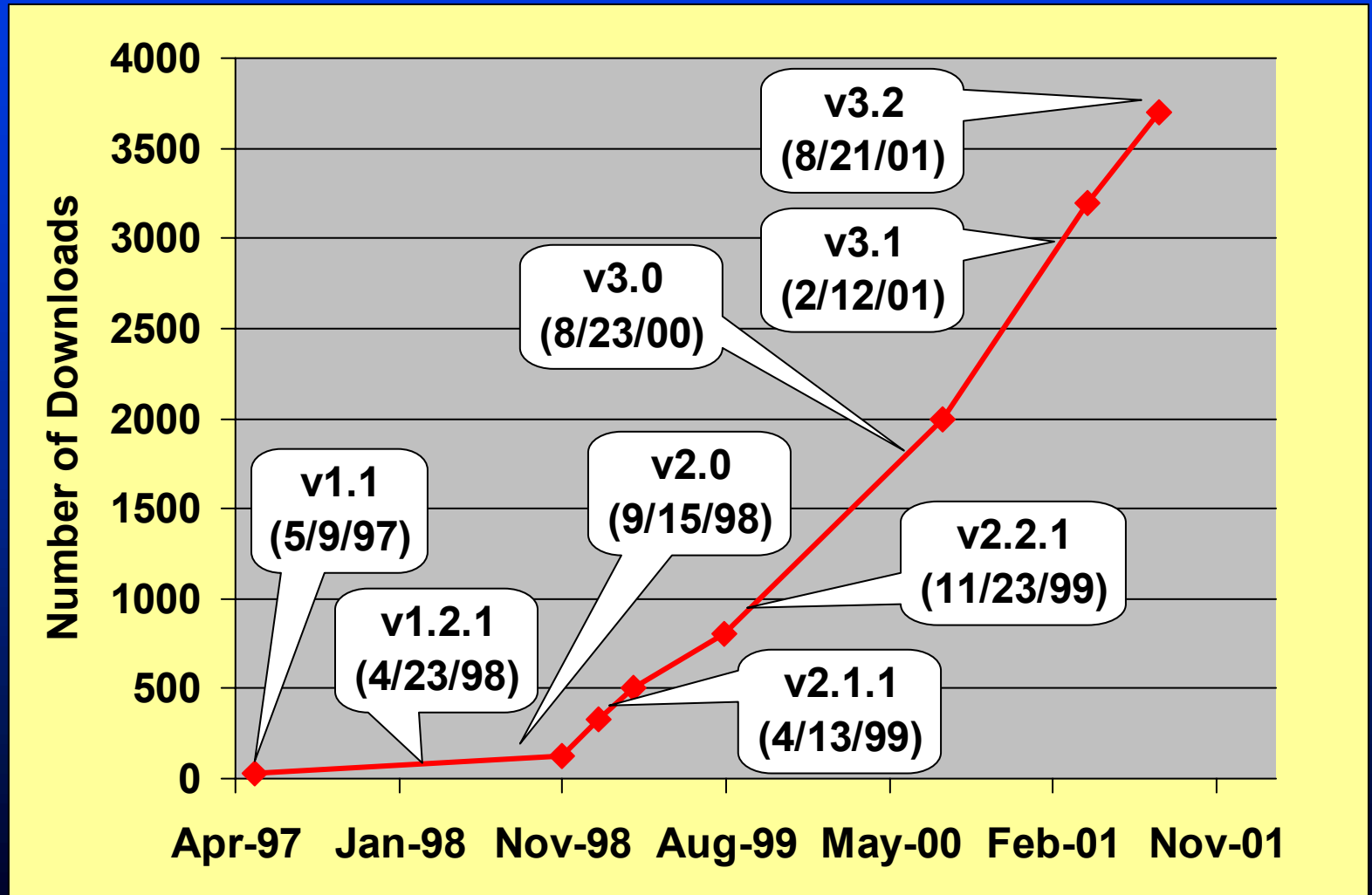
People continue to return for new updates to ADVISOR
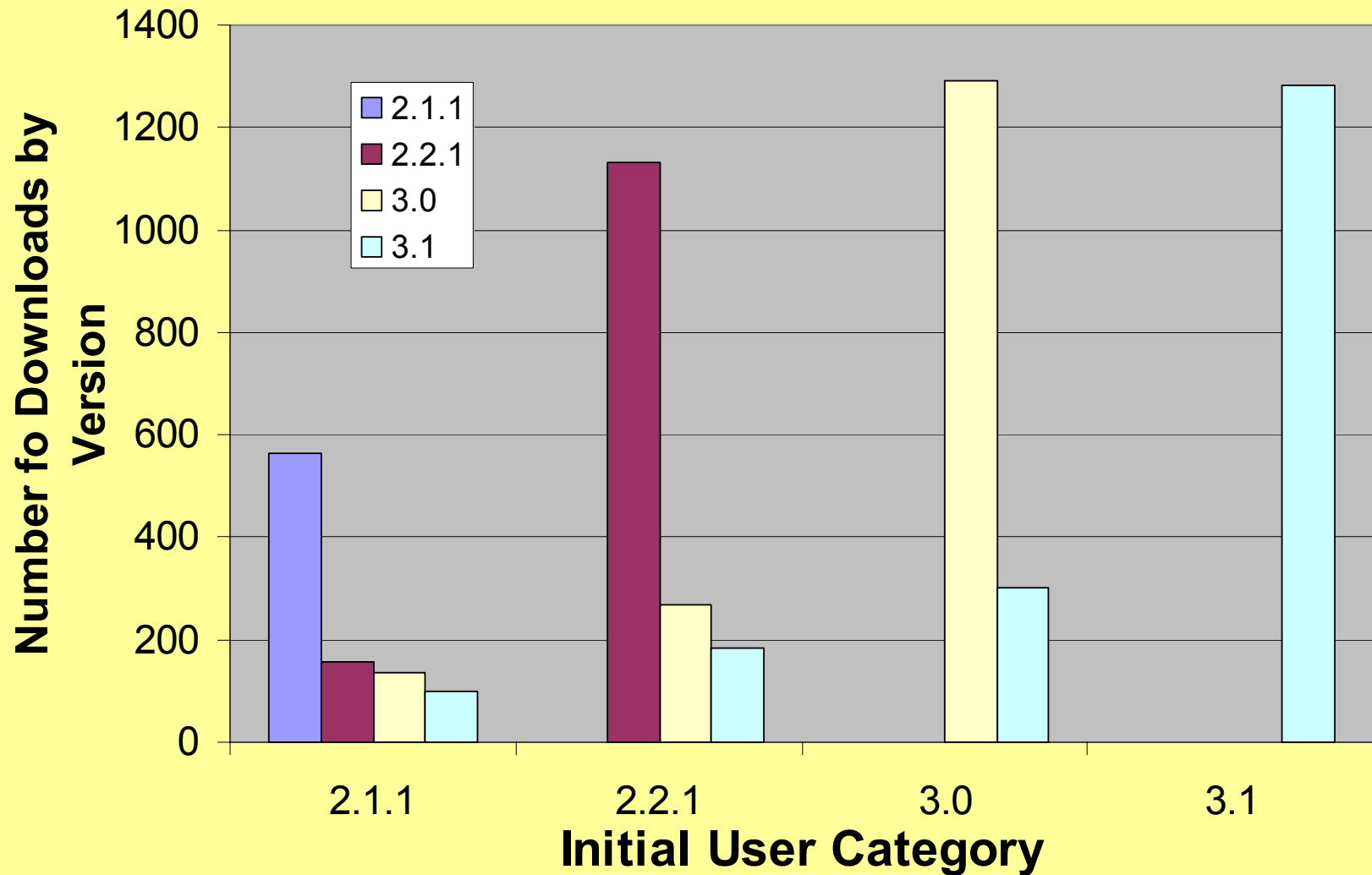
~25% of Users Consistently Return to Download *Next* Version of ADVISOR
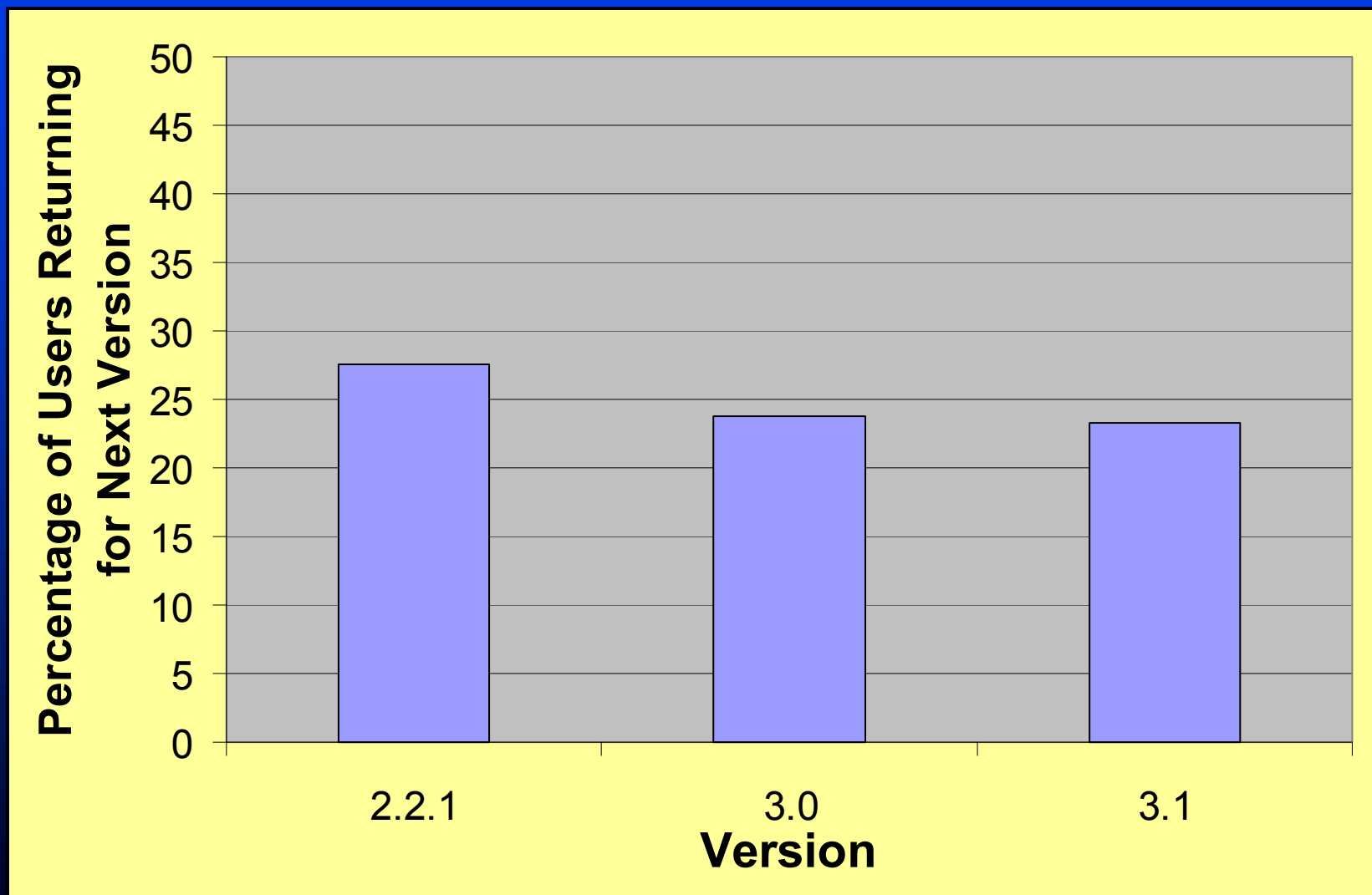
How we use the tool

- **Technical targets analysis**
- Battery trade-off study
- **Fuel cell vehicle optimization**
- Input to battery thermal management
- **Input to auxiliary loads team**

If all targets satisfied fuel economy goals should achieved (based on tech targets)

Composite Fuel Economy (mpgge) vs FY00 and 2004

Legend:
- Parallel w/CIDI
- Fuel Cell Hybrid - Gasoline
- Fuel Cell Hybrid - Hydrogen

Vehicle Performance Target (2004)
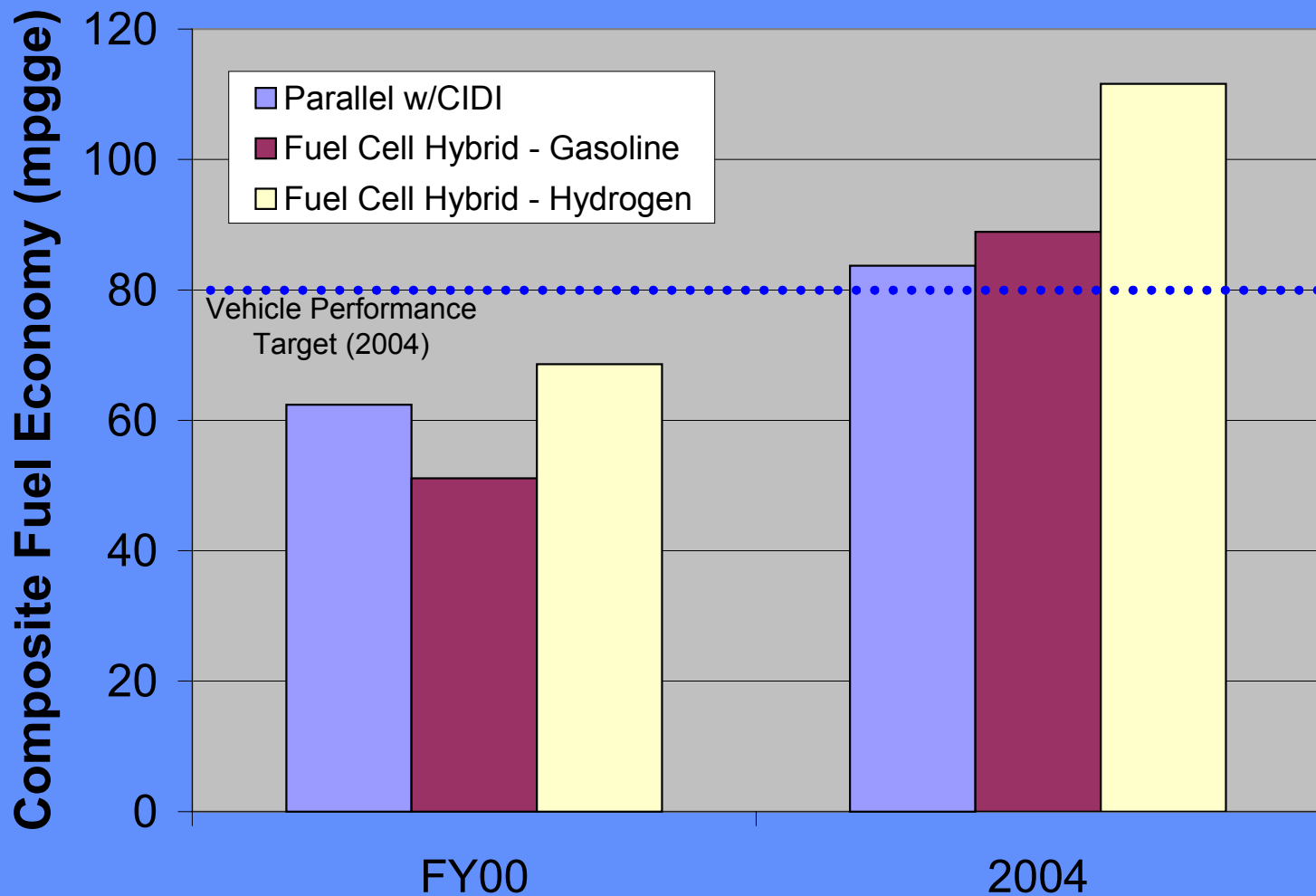
Predicted Vehicle System Mass Breakdown Correlates with Target (based on tech targets)

Vehicle Performance Target (2004)

Mass (kg) axis: 0, 200, 400, 600, 800, 1000, 1200, 1400, 1600

Legend:
- Aftertreatment
- Fuel Converter
- Energy Storage
- Motor/Controller
- Transmission
- Electrical/Interior/Exterior
- Body & Chassis

Categories:
- FY00 Parallel w/CIDI
- FY00 Fuel Cell Hybrid - Gasoline
- FY00 Fuel Cell Hybrid - Hydrogen
- 2004 Parallel w/CIDI
- 2004 Fuel Cell Hybrid - Gasoline
- 2004 Fuel Cell Hybrid - Hydrogen

Optimization Problem Definition

- Objective
  - Maximize fuel economy of fuel cell powered hybrid electric SUV
- Constraints
  - Performance equivalent to comparable conventional vehicle
    - 7 inequality constraints
- 8 Total Design Variables
  - 4 Component Characteristics
    - fuel cell peak power
    - traction motor peak power
    - number of battery modules
    - capacity of battery modules
  - 4 Control Strategy
    - low power fuel cell power cut-off
    - high power fuel cell power cut-off
    - minimum fuel cell off time
    - charge power set point

Vehicle System Optimization for Drive Cycle Fuel Economy Using Multiple Algorithms

Battery size variation was influential in optimal configurations!
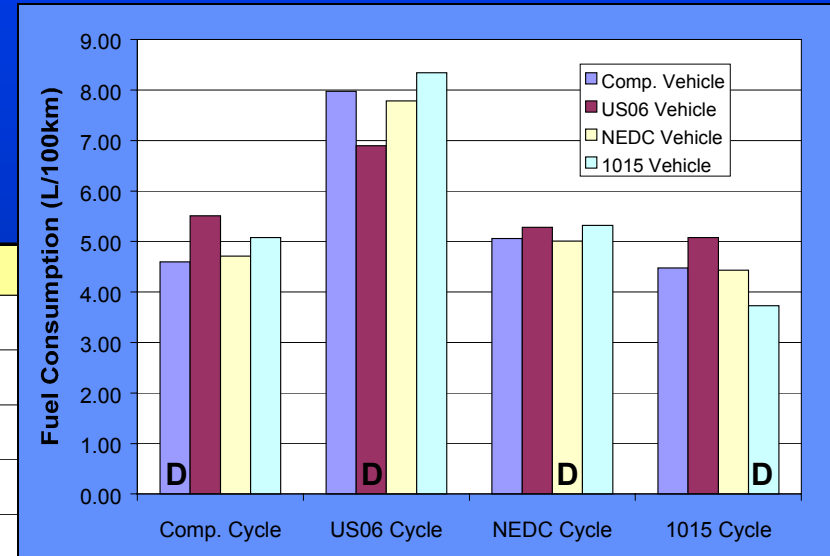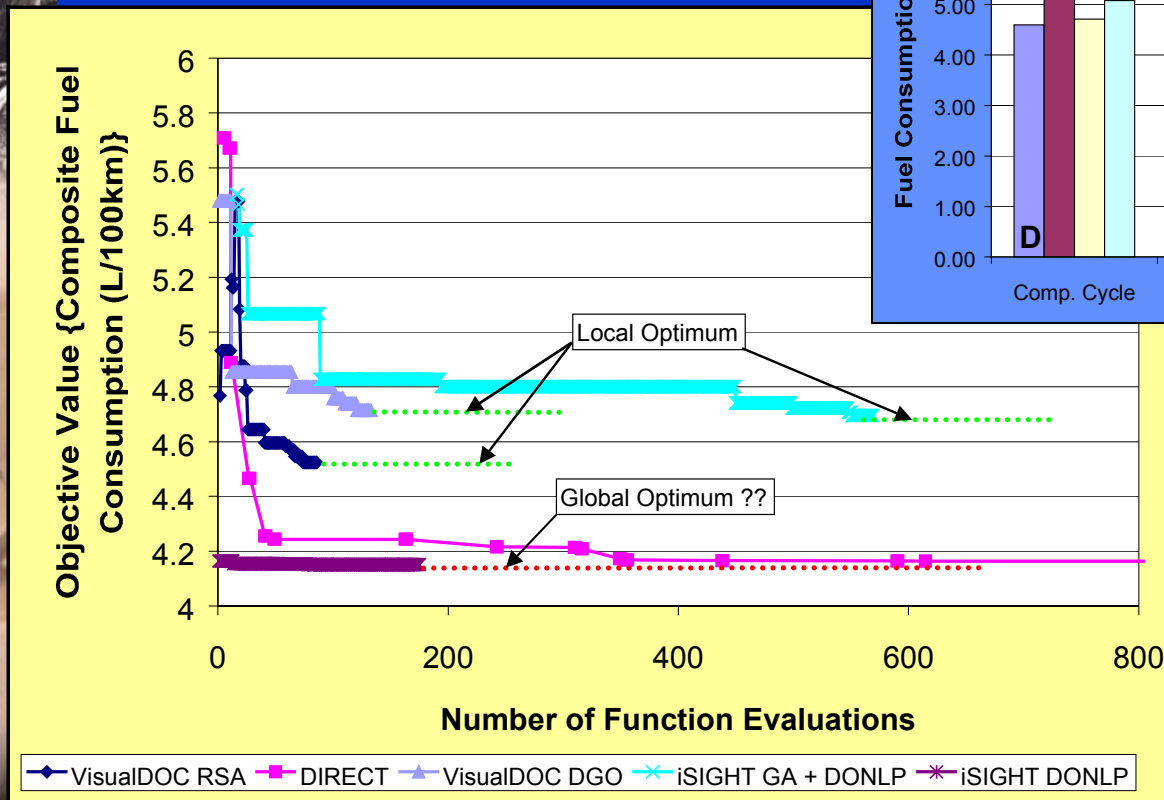
Impacts of Drive Cycle

Fuel Cell SUV Study to be Presented at EVS-18 Conference

- Study highlighted the effects of drive cycle on optimal configuration

- Explored the details of the vehicle configuration

- Based on,
  - Honeywell fuel cell data
  - Ovonic NiMH batteries
  - GE AC induction traction motors

NREL, Center for Transp...

Large Variation in Operating Characteristics of Optimal Configurations
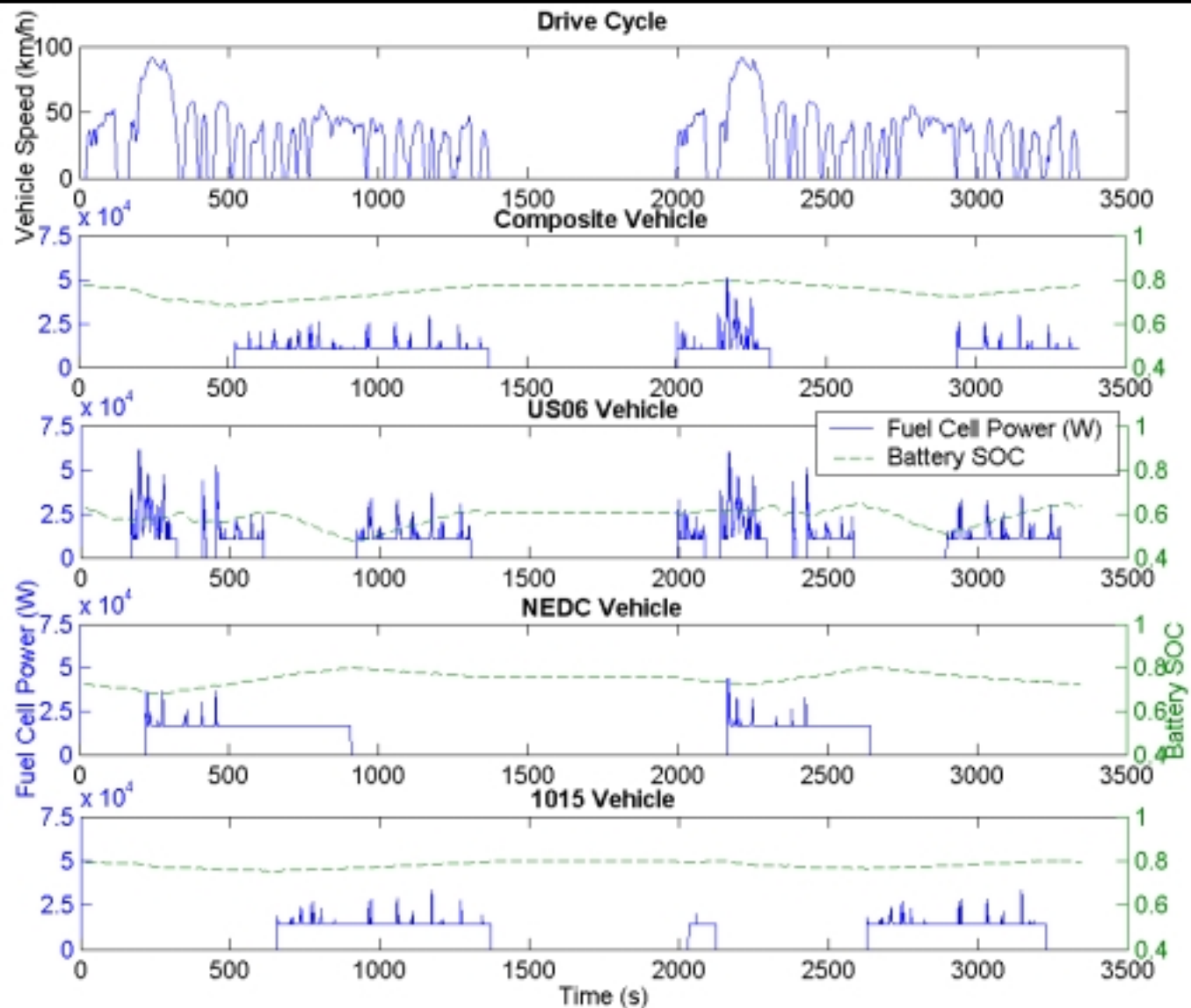
Accessory Loads Have More Impact on Efficient Vehicles
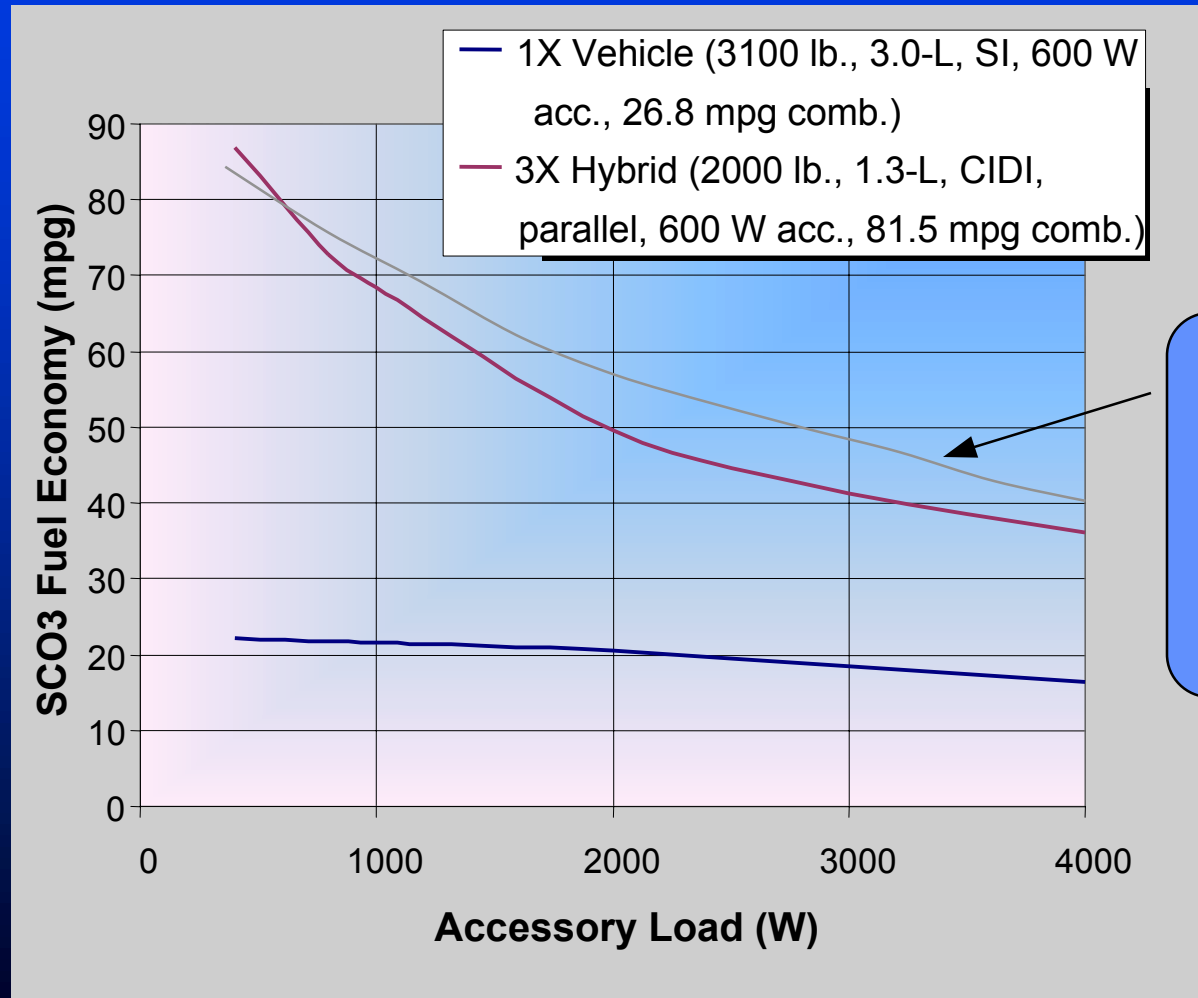
Things to look for in future versions

- Co-simulation with Saber for detailed electric systems
- **Improved system thermal model for fuel cell systems**
- **Transient A/C system model**
- Customizable results screen
- **ADVISORLite**
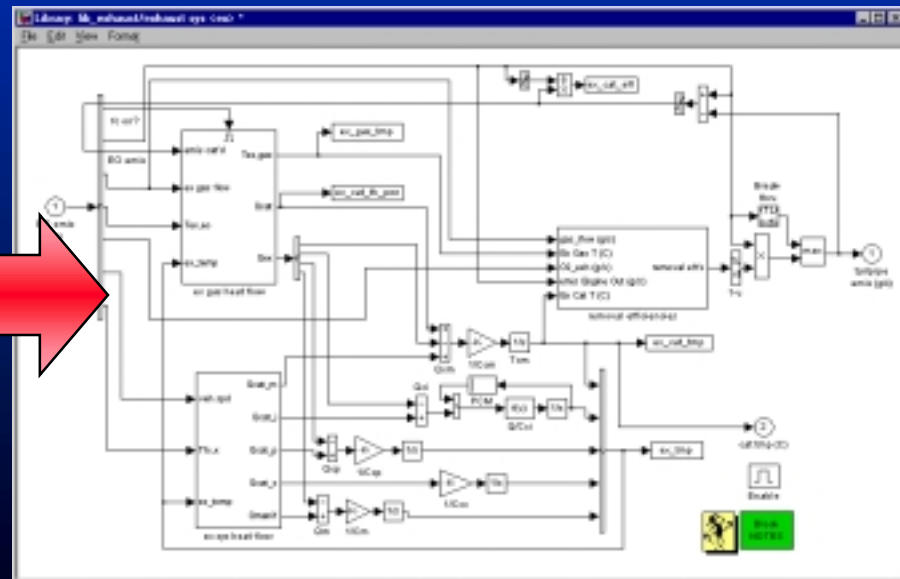- ADVISOR Community web site

Current Fuel Cell Thermal Model Development in Partnership with Virginia Tech

- Similar to existing thermal models for IC engines
- Multi-node thermal network
- Parameterized for flexibility
- Includes conduction, radiation, convection, and phase change (liquid to vapor)
- Work initiated in FY01

Physical Model
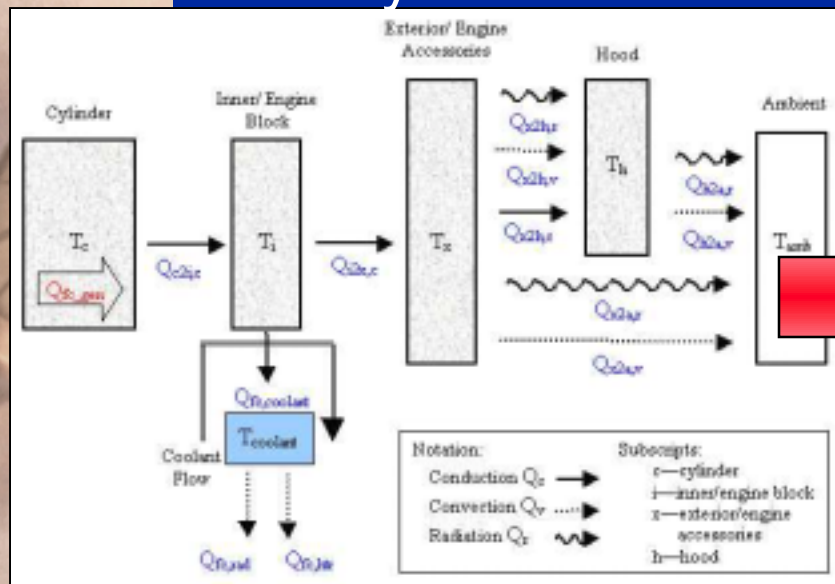
ADVISOR Simulation Model

ADVISOR – Transient A/C - VSOLE

- ADVISOR-SINDA/FLUINT Link Operational
  - Time Synchronization & Variable Exchange Established
  - ADVISOR Interface/Control Completed
  - VSOLE Linkage Developed
  - Co-Simulation & System Optimization Possible

VEHICLE FUEL ECONOMY

ADVISOR

Transient A/C System Model (SINDA/FLUINT)

VEHICLE EMISSIONS

Vehicle Solar Load Estimator (VSOLE)
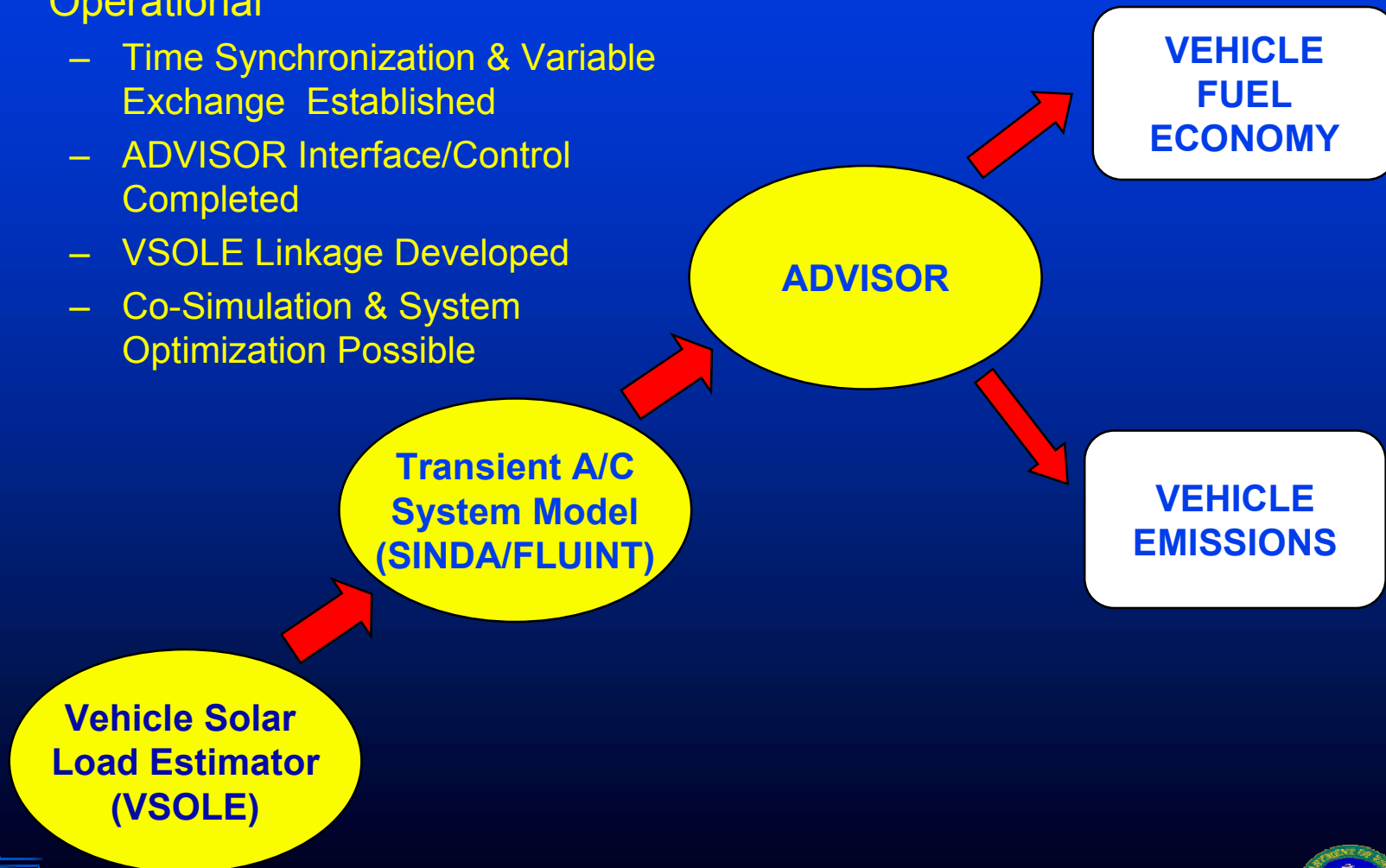
ADVISORLite and ADVISOR Community

Conclusions

- ADVISOR 3.2 has lots of new features and improvements

- We use the tools to answer interesting analysis questions

- The user statistics show that users find value in our software

- Our users help guide the development directions

- Many new features yet to come ...